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Cyclic response of Ottawa sand under different test conditions: Cyclic triaxial, unidirectional and bidirectional direct simple shear

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ABSTRACT: Cyclic direct simple shear (CDSS) and cyclic triaxial (CTX) tests are the most commonly used methods to determine cyclic strength of soils. Cyclic resistance ratio determined from CTX tests is generally corrected to be comparable to that of CDSS test results and the field stress condition for level ground. In this study, CRR values are determined for Ottawa sand using three testing methods: CTX, unidirectional and bidirectional CDSS. CTX specimens were saturated and isotropically consolidated. CDSS specimens were dry and consolidated under presumed K_0 condition and shearing phase was conducted at constant volume. The correction factor (C_r) determined using the results from three different methods is compared with published values. The effect of bidirectional loading on C_r was found to be more complex than a simple 10% reduction coefficient suggested in the literature and warrants further investigation.

1 INTRODUCTION

Cyclic laboratory tests are useful tools for the evaluation of a soil's cyclic strength and stiffness properties. For liquefaction triggering analyses, laboratory tests are generally used in combination with field measurements provided high quality specimens can be retrieved from the site or representative specimens can be reproduced using appropriate reconstitution methods. Cyclic strength of soil is generally represented as the cyclic resistance ratio (CRR), which is the cyclic stress ratio (CSR) required to reach liquefaction at a certain number of cycles. Cyclic direct simple shear (CDSS) and cyclic triaxial (CTX) tests are the two most commonly used laboratory tests to determine cyclic strength of soils. In CTX the specimen is sheared along a 45 to 60 degree plane inclined to the horizontal plane by cycling the axial stress above and below an isotropic consolidation stress. In CDSS the principle shearing direction is on a horizontal plane which resembles that of the vertical incidence of earthquake shear waves propagating upward at a site with level ground. The CDSS test is simpler and faster to run and requires less specimen volume. CTX tests may be more representative of the stresses beneath sloping ground and foundation loads during an earthquake and the principal stresses are better known. The test requires larger specimens. CSR for CTX test (CSR_{CTX}) is defined as:

$$CSR_{CTX} = \frac{\sigma_d}{2\sigma'_c} \tag{1}$$

where σ_d is the deviator stress and σ'_c is the mean effective consolidation stress. CSR for CDSS test (CSR_{CDSS}) is defined as:

$$CSR_{CDSS} = \frac{\tau}{\sigma'_v} \tag{2}$$

where τ is the average shear stress and σ'_v is the average normal stress on the specimen at the end of consolidation.

It has been shown by many that the CSR values causing liquefaction in CTX (CRR_{CTX}) tests are significantly higher than those in CDSS tests (CRR_{CDSS}). Since the loading condition in the

CDSS test is considered more representative of the field conditions for level ground, CRR_{CTX} is modified with a correction factor (C_r) to get comparable conditions. C_r is defined as:

$$C_r = \frac{CRR_{CDSS}}{CRR_{CTX}} \tag{3}$$

where CRR_{CDSS} is the cyclic stress ratio from a CDSS test (Eqn.2) for a selected number of cycles to cause liquefaction (N_L) in the cyclic simple shear test and CRR_{CTX} is the cyclic stress ratio from CTX test (Eqn.1) for the same number of cycles to cause liquefaction in the cyclic triaxial test. This correction factor, C_r was proposed as a function of K_0 by Finn et al. (1971) and Seed & Peacock (1971). The relationship used in this paper is shown in Eqn.4 below:

$$C_r = \frac{1 + 2K_0}{3} \tag{4}$$

Castro (1975), De Alba et al. (1976), Seed (1979), Idriss & Boulanger (2008) and others suggested a correction factor (C_r) ranging between 0.55 – 0.72 based on differences in initial effective stresses in the two test types. For normally consolidated sands K_0 can be assumed to be around 0.45 – 0.5 leading to C_r values from 0.63 – 0.67.

Several studies have examined the effects on cyclic strength of multidirectional loading which occurs during a seismic event. (e.g. Pyke et al. 1974 using shake table tests, Seed 1979 using field data and Ishihara & Yamazaki 1980, Boulanger & Seed 1995, Kammerer et al. 2002 using multidirectional CDSS tests). Most of these studies have shown that the cyclic loading in two orthogonal directions leads to lower cyclic strength for level ground conditions. Idriss & Boulanger (2008) suggested that the cyclic strength needs to be reduced by 10% to include the multidirectional effects. However, Kammerer et al. (2002) suggested that the effects of multidirectional loading are much more complicated to can be represented by a simple reduction factor of 10%.

In this study, results of cyclic tests on Ottawa sand from CTX tests are compared to those of unidirectional and bidirectional constant volume CDSS tests. Additionally, in order to better understand the effects of multidirectional loading on the cyclic strength, specimens were tested in direct simple shear with different loading patterns (rotational, oval, and Figure 8). The findings of this study are compared to the findings of Ishihara & Yamazaki (1980) for Fuji River and Kammerer et al. (2002) on Monterey sand.

2 TESTING EQUIPMENT AND PROGRAM

The CTX device (Figure 1a) used in this study is controlled with feed-forward adaptive control to precisely apply axial loads. The system applies and maintains the axial load using a servo control system coupled with a zero backlash, and a low inertia linear electromechanical actuator. This approach allows the axial load to be controlled to within +/- 5% of the target value. The load is measured using an internal low-profile load-cell with capacity of 4.44 kN

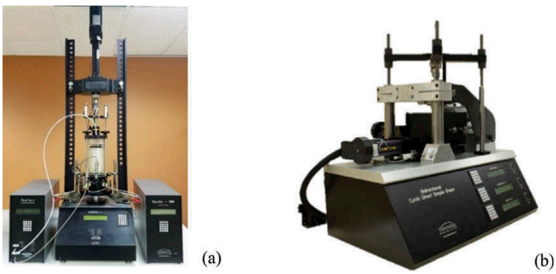

Figure 1. a) CTX and b) BDCDSS equipment used in this study.

and resolution of 0.5 N. The axial displacement is measured using two displacement transducers attached to the top of the chamber with range and resolution of 50 and 0.00075 mm, respectively. The cyclic triaxial equipment is explained in detail in Zehtab et al. (2018).

For direct simple shear tests, a fully automated bidirectional CDSS (BDCDSS) device developed and manufactured by Geocomp Corporation (Zehtab et al. 2019, in press) is used (Figure 1b). The specimen in this device is laterally confined in a latex membrane constrained by Teflon coated stacked aluminum rings. The stacked rings can slide on each other with minimal friction. The device uses independent self-contained, high-speed control and data acquisition systems for each axis (one vertical axis and two horizontal axis). Capacity of the vertical loading frame is 11 kN and is driven in closed loop mode by a micro-stepper system. A low friction, high velocity gearbox transmits the motor's rotary motion to the vertical frame (and to the top cross-bar) in order to apply the vertical load or displacement. Vertical load is measured using a low-profile load-cell with capacity of 4.44 kN and resolution of 0.5 N. Axial displacements are measured using displacement transducers with range and resolution of 25 and 0.00038 mm, respectively. Vertical loading piston is fixed against lateral movement by a support arm, but it is free to move vertically (up and down) through a Teflon bushing with low friction.

The horizontal loading frame has a capacity of 4.44 kN in each direction and are driven by independent closed loop servo motor/actuator systems. Each low friction, high velocity, zero-backlash linear actuating setup transmits low inertia servo motor's motion to the shear box that slides over low friction rollers. BDCDSS uses two sets of independent linear guides and rollers for each direction. Horizontal load is measured using low-profile load-cell with capacity of 0.9 kN and resolution of 0.1 N. Horizontal displacement is measured using a displacement transducer with range and resolution of 50 and 0.00075 mm, respectively. BDCDSS uses a high-speed feed-forward algorithm to actively maintain the height on specimens of different characteristics without loss of control.

Tests in this study were conducted on poorly graded ASTM C778–F65, Ottawa Sand with specific gravity (G_s) of 2.65 and e_{max} and e_{min} of 0.84 and 0.52, respectively. Cylindrical specimens of 63.5 mm diameter and height of 25.4 mm for CDSS and 71.12 mm diameter and height of 151.64 mm for CTX with relative density (D_r) of 40–45% were prepared using dry air pluviation. In CTX tests, sand specimens were back pressure saturated and isotropically consolidated to the effective stresses of 100 kPa and 600 kPa. In CDSS tests, dry sand specimens were consolidated to K_0 condition under the vertical effective stresses of 150 kPa and 900 kPa respectively, corresponding to the same mean effective stresses with CTX tests. K_0 for sand is assumed to be 0.5.

The testing program included 10 CTX tests, 11 unidirectional and 24 bidirectional CDSS tests with three different loading patterns. Figure 2, summarizes all the tests in the experimental program with various loading patterns.

The unidirectional tests were performed by shearing the specimen in X axis where the Y axis is constrained from any horizontal movement. Bidirectional tests were performed under 3

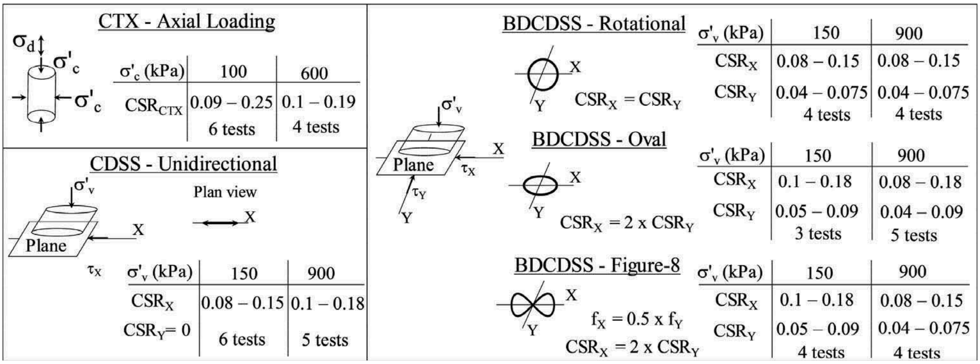

Figure 2. Testing program for the different loading patterns.

different loading patterns including rotational, where the same CSR amplitude is applied to the two perpendicular horizontal axis with a phase angle of 90°; oval, where the amplitude of CSR in X axis is twice of the CSR amplitude in Y axis; Figure 8, where the two axis are sheared with different frequencies and amplitude (Figure 2). All the unidirectional and bidirectional CDSS tests are run with cycling about zero shear stress to model level ground conditions. Liquefaction is defined by either the excess pore pressure ratio (r_u) reaching unity or when the first cycle after the peak-to-peak shear strain becomes equal or greater than 7.5%. r_u can be determined as:

$$r_u = \frac{\sigma_{ps} - \sigma_v}{\sigma_{ps}} \tag{5}$$

where σ_{ps} is the pre-shear value of vertical stress. The strain accumulation can be very fast within a cycle as the soil approaches liquefaction. All the CDSS and BDCDSS tests were run on the dry Ottawa sand specimens under constant volume condition with active height control. The drop in σ_v is assumed to be equivalent to the pore pressure that would have been developed if the specimen was saturated while shearing in undrained condition (Dyvik et al. 1987). This assumption is verified with experimental results published by Dyvik et al. (1987) for clays and by Finn (1985) for sands. The axial strains during cyclic simple shear were kept under ±0.03% to eliminate the effects of inadequate volume control which leads to partially drained condition and a corresponding increase in measured cyclic strength as reported by Zehtab et al. (2019), in press.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 *Cyclic response of Ottawa sand under unidirectional loading*

CRR for Ottawa sand at two different effective stress levels are determined using CTX and unidirectional CDSS tests. CRR, determined from these tests can be represented with a power function in the form of:

$$\mathrm{CRR} = a\, N_L^{-b} \tag{6}$$

where constant b depends on the type of the sand and constant a depends on wide range of factors such as relative density, effective stress, and etc. Figure 3 shows the CTX and CDSS results and the power function of Eqn. 6, fit to the experimental results.

As expected for the same number of cycles of shearing, the CRR values obtained from CTX test are higher than that of the unidirectional CDSS tests data due to the differences between the stress paths of these two tests. Figure 4 shows the values of C_r calculated using Eqn. 3 for the experimental data. The C_r values slightly vary for different number of cycles for the same mean effective stress.

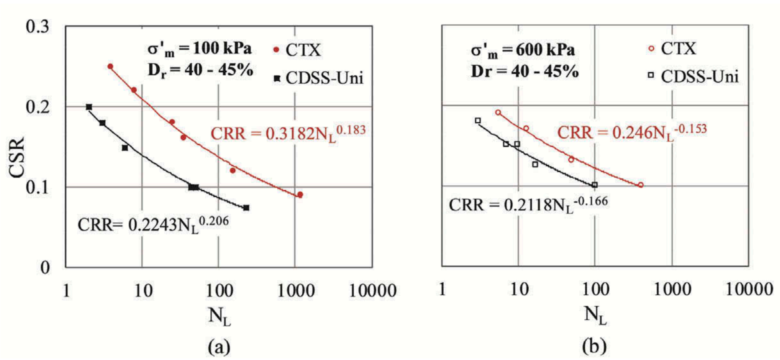

Figure 3. Comparison of CTX and CDSS tests; a) 100 kPa b) 600 kPa.

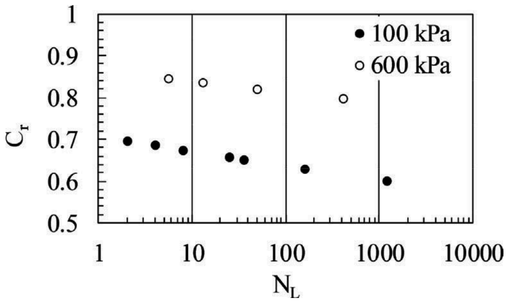

Figure 4. C_r values for 2 different effective stress a levels as function of number of cycles to liquefaction.

This is also observed by De Alba et al. (1976). C_r for σ'_c = 100 kPa is between 0.60–0.70, a range which the value for C_r, if determined using Eqn. 4 for K_0=0.5, is within. However, for σ'_c = 600 kPa, C_r is between 0.80–0.84 which is higher than C_r=0.67 from Eqn. 4 for K_0=0.5. Harder (1988) reported that C_r was only dependent on relative density and the different definitions of liquefaction (r_u =1 or occurrence of peak to peak shear strain of 5, 10, and 15%). The difference in C_r observed in this study seems to point at dependency of C_r to the mean effective stress in which case it needs further investigation.

3.2 *Cyclic response of Ottawa sand under bidirectional loading*

The effect of multidirectional loading on the cyclic response of Ottawa sand is investigated by addition of a second shearing direction to the CDSS tests. The plan view of the different loading patterns, detailed in Figure 2, and the cyclic response of soil to these loads are shown in Figure 5.

Results show a change in both number of cycles to liquefaction and pore pressure build up. As shown in Figure 5, the resulting strain accumulation is correlated to the shape of loading pattern applied on the specimen. Under the rotational loading pattern, strain accumulation in both axes is symmetrical and reaches up to almost 10% on both axes.

Under the oval loading pattern, strain accumulation in Y axis is less since CSR in Y axis is less than on the X-axis. (CSR_X/CSR_Y=0.5). Strain accumulation under the Figure 8 loading pattern is different from the other loading patterns. The strain accumulation is much smaller in Y axis even though the CSR ratio (CSR_X/CSR_Y=0.5) is similar to the oval loading pattern. This observation is different from the findings of Kammerer et al. (2002) where the effect of direction was found to be greater for the Figure 8 loading pattern. This effect requires further investigation.

Figure 5 also shows that for the rotational and oval bidirectional loading patterns, r_u is limited to a value ($r_{u,Lim}$) that is less than 1. The figure shows one set of data from each loading pattern as an example. For all the bidirectional tests, $r_{u,Lim}$ data is in the range of 0.78 to 0.98. The multidirectional effect is more prominent for rotational and oval loading where lowest value of $r_{u,Lim}$ is 0.78. However, for the Figure 8 loading pattern, $r_{u,Lim}$ is 0.98 approaches 1 similar to the unidirectional CDSS tests. The phenomenon of limited pore pressure build up was also observed by Ishihara & Yamazaki (1980) and Kammerer et al. (2004). This behavior results from that fact that shear stresses never pass through zero and reverse direction in the rotational and oval loading patterns whereas they do in the Figure 8 loading pattern.

Introduction of a second shearing direction is observed to influence the number of cycles to liquefaction (N_L). Figure 6 shows the data from bidirectional tests compared to the relationship created by fitting the power function of Eqn. 6 to unidirectional tests data for both sets of effective stresses. As shown in Figure 6, CRR for Ottawa sand is lower under bidirectional loading compared to unidirectional loading for the same number of cycles. This observation is consistent with the various previously published studies (e.g. Pyke et al. 1974, De Alba et al. 1976, Seed 1979; Ishihara & Yamazaki 1980, Boulanger & Seed 1995; Kammerer et al. 2002). It is also observed that the effect of the second direction is influenced by the loading pattern.

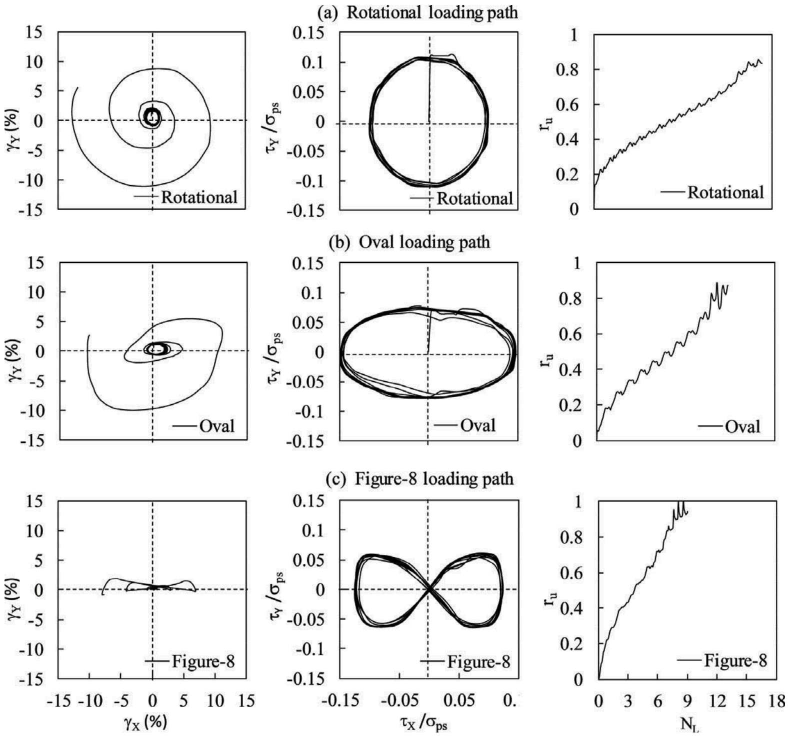

Figure 5. Example of the results from different loading patterns for bidirectional CDSS tests.

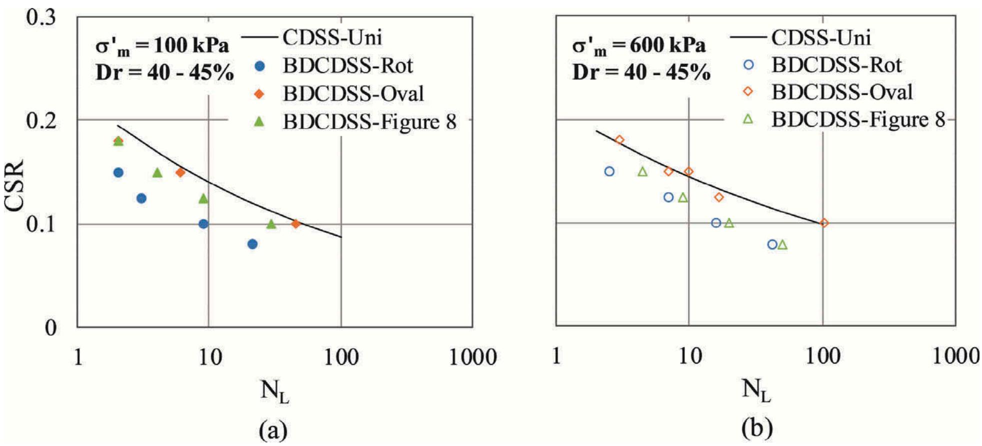

Figure 6. Comparison of unidirectional and bidirectional cyclic simple shear tests a) 100 kPa b) 600 kPa.

Under rotational loading pattern the reduction in CRR is more prominent whereas in oval and Figure 8 loading patterns, the CRR values are very close to those of unidirectional CDSS tests. This observation contradicts with the findings of Ishihara & Yamazaki (1980) where CSR values determined for the tests with oval loading pattern were substantially lower than those of the unidirectional tests. It is worth noting that the bidirectional tests of Ishihara & Yamazaki (1980) were conducted under isotropically consolidated condition where cell pressure was controlled throughout the tests whereas in this study the specimens are consolidated

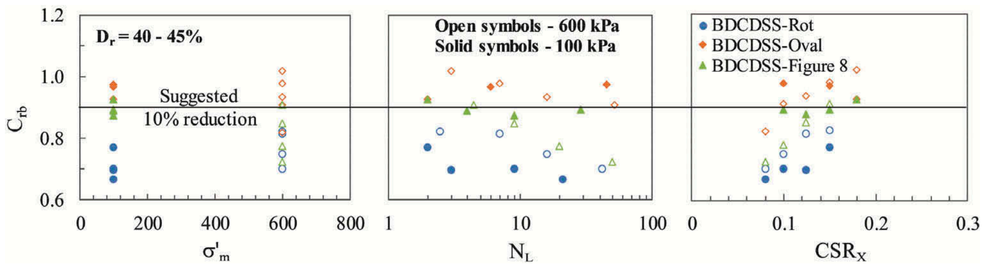

Figure 7. C_{rb} for different bidirectional loading patterns.

under K_0 condition and the shearing phase is conducted under constant volume (equivalent undrained CDSS).

In order to quantify the effect of bidirectional loading on CRR values another correction factor (C_{rb}) can be used as:

$$Crb = \frac{CRR_B}{CRR_{EQ}} \tag{7}$$

where CRR_B is the CSR that caused liquefaction under bidirectional loading and CRR_{EQ} is the equivalent CSR that would cause liquefaction under unidirectional loading for the same number of cycles.

CRR_{EQ} is determined using the power function of Eqn. 6, fitted to the data for unidirectional tests where a=0.2243 and b=-0.206 for σ'_c = 100 kPa and a=0.2118 and b=-0.166 for σ'_c = 600 kPa. Figure 7 shows the calculated C_{rb} values against the effective stress, number of cycles to liquefaction, and CSR in X direction.

As shown in Figure 7 C_{rb} does not show a clear dependence on the effective stress and number of cycles to liquefaction and is scattered between 0.67 and 1.02 but seem to increase with the increasing CSR_X values. It can also be deduced from Figure 7 that the suggested extra 10% reduction in order to account for the effects of multidirectional loading by Idriss & Boulanger (2008) overly simplifies the complex effects of loading patterns and may lead to both under and overestimating the cyclic strength of Ottawa sand. This is in line with the findings of Kammerer et al. (2004) for Sacramento river sand where the C_r under multidirectional loading was found to be between 0.61–1.3 for level ground tests.

4 CONCLUSIONS

Cyclic laboratory tests are an effective way of conducting liquefaction triggering analyses when high quality specimens are retrieved from the site or representative specimens can be prepared using appropriate reconstitution methods. This is because the specimen conditions can be determined, and the applied stresses are controlled. However, the limitations of each testing method in representing the field conditions requires careful attention. For cyclic loading current state of practice includes using C_r to correct the CRR values determined using CTX tests in order to make them representative of the field conditions for level ground cases. Also a further 10% reduction is used in order the incorporate the effects multidirectional loading that occurs during a seismic event. In this study validity of the extra 10% correction in order to account for the effects of multidirectional loading is examined using CTX, unidirectional and bidirectional CDSS tests with different loading patterns on Ottawa sand with D_r of 40–45%.

CSR values determined from CTX test are compared to those from unidirectional CDSS tests. C_r for CTX test is found to be consistent with the suggested values as a function of K_0 but also dependent on the effective stress level. The possible correlation of C_r and the effective stress needs further investigation where specimens of different properties are tested under different effective stresses.

Using three different bidirectional loading patterns (rotational, oval, and Figure 8) the multidirectional loading was observed to have an effect on both number of cycles to liquefaction and pore pressure generation. r_u under bidirectional loading did not reach 1 but instead a value lower than 1 ($r_{u,Lim}$). It was measured as low as 0.78 under rotational loading and high CSR values.

A correction factor (C_{rb}) was determined to account for the effects of bidirectional loading on the cyclic strength. Based on the values determined for C_{rb}, the effect of bidirectional loading on the cyclic strength against liquefaction is very scattered and should not be consolidated in a simple 10% extra reduction factor as suggested by Idriss & Boulanger (2008). C_{rb} values do not show any distinct correlation with the effective stress or number of cycles to liquefaction but are found to be increasing with higher CSR values. This means at higher CSRs the 10% reduction factor may underestimate the cyclic strength. More importantly at lower CSRs, C_{rb} values are as low as 0.67 where 10% reduction factor may be overestimating the cyclic strength. The results of this study show a need for further investigation of the multidirectional loading effects on the cyclic strength of soils.

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