Proceedings of the 11th ANZ Young Geotechnical Professionals Conference – 11YGPC
Queenstown, New Zealand
25 – 28 October 2016

Effect of Pre-Shearing during Cyclic Simple Shear Testing of Clean Sand for Liquefaction Analyses

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ABSTRACT

The undrained cyclic direct simple shear test (CSS) is an advanced laboratory method well-suited to characterising the in-situ liquefaction resistance of clean and silty sands. This is due to it approximating the one-dimensional consolidation that occurs beneath level ground, and the shear deformations that develop in a soil mass during earthquake shaking. Currently however there is no recognised international standard for this test, which can lead to significant cyclic resistance ratio (CRR) errors being observed when factors such as the sand-apparatus interface and induced stress concentrations are not properly considered. Thus, while CSS testing may be employed as a critical component of detailed liquefaction analyses for important geotechnical projects, the testing itself must be executed with care and guidance. To further clarify CSS testing methodology, this paper systematically examines the effect drained cyclic pre-shearing has on the undrained cyclic resistance of Toyoura sand. The results from this study suggest pre-shearing clean sand CSS specimens under drained cyclic loading conditions, before carrying out undrained cyclic testing, produces CRR values that may be considered reasonably representative of in-situ cyclic response. Conversely, a lack of pre-shearing is shown to produce CRRs approximately 20 % lower in value, which would lead to unnecessary conservativism in design when undertaking detailed liquefaction assessments.

Keywords: liquefaction, undrained cyclic simple shear, drained cyclic pre-shearing, Toyoura sand

1 INTRODUCTION

Advanced laboratory testing of soils can form a critical component of detailed liquefaction analyses for important and/or unique geotechnical projects. The undrained cyclic direct simple shear test (CSS) is one laboratory method well-suited to characterising the in-situ liquefaction resistance of sandy soils. This is due to it approximating the one-dimensional consolidation that occurs beneath level ground, as well as the shear deformations that develop in a soil mass during earthquake shaking (Idriss and Boulanger 2008). When undisturbed samples from the field are tested in an NGI-type CSS apparatus (Bjerrum and Landva 1966), practical advantages over the often-used undrained cyclic triaxial test include the use of shorter specimens (typically 20 mm in height), which enables a greater number of tests to be performed per in-situ sample, and the ability to test specimens in a non-saturated state via the ‘constant volume’ condition (Dyvik et al. 1987), avoiding the need for time-consuming saturation.

The CSS test does however come with limitations. While issues such as stress and strain non-uniformities have been summarised in the literature (Boulanger et al. 1993), a noticeable practical problem for laboratories is the lack of an internationally-recognised test standard for performing CSS tests on sandy soils. Although ASTM D-6528–07 (ASTM International 2007) is widely referred to when performing direct simple shear tests, this standard was published to guide monotonic testing of cohesive soils only, and hence excludes important considerations for the cyclic testing of sandy soils that are otherwise discussed in the geotechnical literature. This means laboratories may conduct CSS tests without sufficient care and guidance, and subsequently estimate cyclic resistance ratios (CRR) that exhibit significant error. Note CRR is defined in this paper as the cyclic stress ratio (CSR) required for a double amplitude shear strain, γ_{DA}, of 15 % to be reached in 10 load cycles.

1.1 Drained cyclic pre-shearing during CSS tests on sandy soils

One CSS test consideration not included in any widely-available test standard, but discussed in literature relating to the laboratory testing of soils for offshore geotechnical engineering projects, is the effect a drained cyclic pre-shearing test stage can have on the CRR of sand when performed prior to undrained cyclic loading. Such a drained pre-shearing stage has typically consisted of 400 load cycles being applied at a stress ratio of $\tau_{cyc}/\sigma'_{vc} \approx 0.04$ to 0.05, while the effective vertical consolidation stress, σ'_{vc}, is maintained constant (Finnie et al. 1999, Andersen 2009). It has been suggested by Andersen (2009) that the ultimate effect of this drained pre-shearing is an increase in the measured CRR of approximately 5 % to 25 %, with improved seating at the sand-apparatus interface, levelling out of stress concentrations induced during initial consolidation, increase in the horizontal stress, and changing of soil fabric providing mechanisms for the CRR increase. Randolph et al. (2005) have made similar comments, with drained pre-shearing procedures being developed in Australian laboratories to minimise specimen reconstitution and bedding effects. To date however there has been no systematic study detailing the effect drained pre-shearing has on the CRR of sands.

Given the suitability of CSS testing for use in liquefaction analyses, this paper systematically examines the effect drained cyclic pre-shearing has on the CSS response of Toyoura sand reconstituted to medium density. Toyoura sand was chosen given its long history of testing in Japanese laboratories as part of liquefaction studies, and cyclic data obtained from this study is subsequently compared with that from high-quality undrained cyclic simple shear tests previously performed on Toyoura sand in the hollow cylinder (HC) apparatus. The high-quality HC data is henceforth assumed to be a reliable benchmark when assessing how representative the data obtained from the CSS apparatus may be of in-situ response. It is however important to note that potential effects of differing soil fabric between in-situ and reconstituted states on the CRR are not specifically addressed in this paper.

2 LABORATORY TESTING

A total of ten undrained CSS tests were performed on reconstituted Toyoura sand specimens as part of this study. Details regarding the laboratory tests are given in the following sections.

2.1 Cyclic direct simple shear test apparatus

All tests were performed within a commercially-available NGI-type CSS apparatus. Full apparatus details can be found in the manufacturer’s documentation (GDS Instruments 2015), however important aspects of the apparatus relevant to this study include: (i) Lateral specimen restraint was provided by a stack of Teflon-coated rings; (ii) Sintered-steel porous discs provided the sand-apparatus interface, and contained triangular-shaped ridges (1 mm in height) oriented perpendicular to the shearing direction; (iii) A 5 mm range LVDT was mounted directly between top and base specimen platens to accurately measure small-strain horizontal deformations; and (iv) Specimen height was actively maintained constant during undrained cyclic loading via feedback from a 5 mm range LVDT measuring vertical deformations.

2.2 Specimen preparation

The test specimens, nominally 70.4 mm in diameter and 18.3 mm in height, were reconstituted to approximately 50 % relative density, D_r, using a moist-tamping technique similar to that described in the literature (Ladd 1978). The moist sand was placed and tamped directly into a mould set up on the specimen base platen, which consisted of a latex membrane, the Teflon-coated ring stack, and an aluminium split mould. A small vacuum was applied through the split mould to pull the membrane against the ring stack, enabling the sand to be tamped across the full specimen diameter. The specific gravity, and maximum and minimum void ratios, e_{max} and e_{min}, of the Toyoura sand tested in this study were taken to be 2.65, 0.988 and 0.616 respectively (Zlatović 1994).

2.3 Test procedure

After securing the test specimen in the CSS apparatus, a vertical effective stress $\sigma'_v \approx 20$ kPa was applied while 150 mL of de-aired water was percolated through the sand. This was carried out to ensure no suction-related stresses were present. The specimen was then consolidated at $\sigma'_{vc} \approx 100$ kPa for at least one hour, before drained cyclic pre-shearing was performed. Here a stress ratio of $\tau_{cyc}/\sigma'_{vc} \approx 0.045$ was applied for a number of load cycles, $N_{c,ps}$, ranging from zero (i.e., no pre-shearing) to 1600. After pre-shearing, the specimen was left to consolidate at $\sigma'_{vc} \approx 100$ kPa for at least one hour, before undrained cyclic loading at a specified cyclic stress ratio (CSR) was executed at a loading frequency of 0.1 Hz. The number of load cycles required to reach failure, N_f, was defined as those taken to first reach a double amplitude shear strain, γ_{DA}, of 15 %. The CSR was defined as being equal to τ_{cyc}/p'_c, where τ_{cyc} = single amplitude horizontal shear stress and p'_c = mean effective stress.

2.4 Test results

Table 1 summarises the CSS tests performed on the reconstituted Toyoura sand specimens. Note the horizontal effective stress following consolidation and pre-shearing, σ'_{hc}, was estimated from $\sigma'_{hc} = K_0.\sigma'_{vc}$, assuming $K_0 = 1 - \sin\varphi'$, and $\varphi' \approx 34$ ° for Toyuora sand prepared to $D_r \approx 50$ % (Yoshimi et al. 1978). The mean effective stress, p'_c, was estimated from $p'_c = (\sigma'_{vc} + 2.\sigma'_{hc})/3$. $D_{r,vc}$ represents the specimen relative density following initial consolidation, while e_{vcps} and $D_{r,vcps}$ respectively denote the specimen void ratio and relative density following pre-shearing. Typical CSS response of the Toyoura sand is shown in Figure 1(a) – (d), obtained from Test 7. Note the circle in each plot highlights the point at which N_f was reached.

Table 1. Summary of undrained cyclic simple shear tests on Toyoura sand specimens

Test	σ'_{vc} (kPa)	σ'_{hc} (kPa)	p'_c (kPa)	$D_{r,vc}$ (%)	e_{vcps}	$D_{r,vcps}$ (%)	$N_{c,ps}$	CSR	N_f
1	99	46	62	45	0.821	45	0	0.197	4.2
2	99	44	62	47	0.813	47	0	0.142	11.6
3	99	44	62	44	0.824	44	10	0.142	12.8
4	99	44	62	47	0.813	47	100	0.142	26.2
5	105	44	66	47	0.809	48	400	0.251	3.6
6	99	44	62	45	0.817	46	400	0.197	7.7
7	99	44	62	50	0.798	51	400	0.164	16.2
8	99	44	62	46	0.817	46	400	0.142	32.7
9	99	44	62	44	0.817	46	800	0.142	32.2
10	99	44	62	45	0.817	46	1600	0.142	32.2

3 DISCUSSION

3.1 Effect of number of pre-shearing load cycles on relative density

The effect of drained cyclic pre-shearing on the Toyoura sand specimens was firstly investigated by checking the variation in relative density before and after the pre-shearing stage. From observing the difference in $D_{r,vc}$ and $D_{r,vcps}$ values in Table 1, it is noted D_r increased by 0 % to 2 % between the beginning and end of pre-shearing. This increase is relatively insignificant when compared with the 6 % variation in $D_{r,vc}$ observed across the 10 test specimens, suggesting specimen reconstitution has a more pronounced effect on the post-consolidation D_r than pre-shearing. This finding is consistent with the literature, where volume reduction during pre-shearing is described as generally being small (Andersen 2009).

The single amplitude shear strain recorded during each pre-shearing load cycle, γ_{cyc}, was also investigated. Here each specimen underwent an approximately consistent $\gamma_{cyc} \approx \pm 0.02$ % during each cycle, which is of the order of the elastic threshold for soils (Ishihara 1996). This suggests the sand experienced only limited plastic deformation, which is consistent with the limited change in D_r.

3.2 Effect of number of pre-shearing load cycles on cyclic resistance

The effect of pre-shearing was secondly investigated by comparing the number of undrained cyclic load cycles required to reach failure, N_f, with the number of applied pre-shearing cycles, $N_{c,ps}$. This comparison in displayed in Figure 2, with a CSR = 0.142 applied to all specimens. It is firstly noted from Figure 2 that N_f increased from 11.6 to 32.7 as $N_{c,ps}$ increased from 0 to 400. This clearly demonstrates an increased resistance to undrained cyclic loading provided by pre-shearing, consistent with the ultimate effect of pre-shearing described in the literature (Andersen 2009). This is further quantified in Section 3.3, in which CRR values are directly compared.

A second trend observed from Figure 2 is that N_f does not increase as $N_{c,ps}$ is raised further from 400 to 1600. Instead, the value of N_f remains approximately constant, varying by only 0.5. While there is limited data available in the literature for comparison, this result is broadly consistent with Andersen (2009), in which 'Soil 26', also prepared to 50 % D_r, shows a limited increase in cyclic strength for N_f = 10 when $N_{c,ps}$ is increased by an order of magnitude (from 400 to 4000). Overall this finding is considered physically reasonable, given prolonged cyclic loading at a shear strain amplitude near the elastic threshold is unlikely to continue resulting in significant plastic straining.

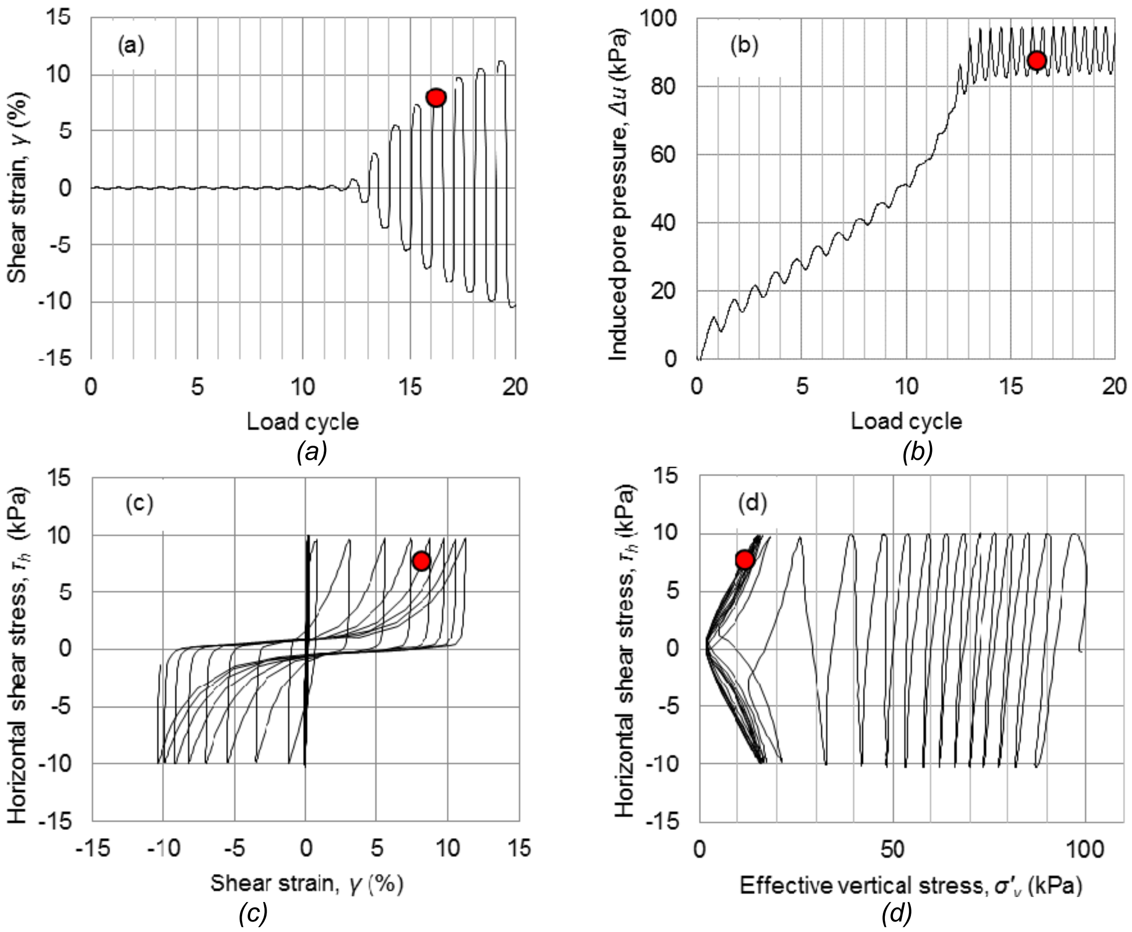

Figure 1. (a) – (d). Typical undrained cyclic simple shear response of the Toyoura sand.

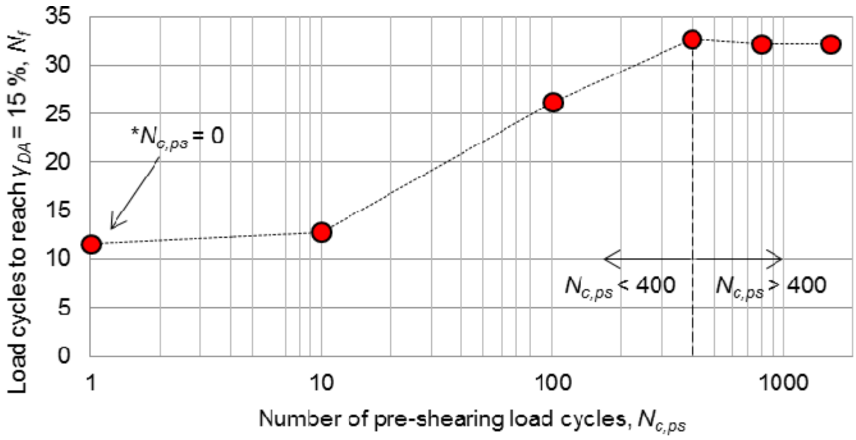

Figure 2. Effect of drained cyclic pre-shearing on the cyclic resistance of Toyoura sand.

3.3 Comparisons with data obtained from hollow cylinder testing

The effect of pre-shearing was lastly investigated by comparing the cyclic resistance data obtained from this study with that from five previous studies which employed the hollow cylinder apparatus (HC) to perform high-quality undrained cyclic simple shear tests on saturated Toyoura sand specimens prepared to D_r ≈ 50 % (Tatsuoka et al. 1982, Tatsuoka et al. 1986, Koseki et al. 2005, Kiyota et al. 2008, Chiaro et al. 2012). A summary of this HC testing is provided in Table 2, while Figure 3 compares the cyclic resistance data from six of the Toyoura sand specimens tested in this study ($N_{c,ps}$ = 0 or 400) with that from the HC testing. In this figure three clear trends are observed. Firstly, the CRR of the Toyoura sand specimens tested in this study significantly decreases when no pre-shearing is applied. Here the CRR = 0.184 for $N_{c,ps}$ = 400, while the CRR = 0.147 for no pre-shearing. This corresponds to a 20 % decrease in CRR when pre-shearing is not employed, which is consistent with the effect of pre-shearing on cyclic resistance as reported by Andersen (2009).

Table 2. Undrained cyclic simple shear tests previously performed in the HC apparatus

Reference	Reconstitution	Failure definition	$\sigma'_{hc}/\sigma'_{vc}$ [b]	p'_c (kPa)	D_r (%)
Tatsuoka et al. 1982	Air-pluviation	γ_{DA} = 15 %	1.0	98	50
Tatsuoka et al. 1986	Moist-tamping	γ_{DA} = 15 %	$0.52e_i$ [a]	98	50
Koseki et al. 2005	Air-pluviation	γ_{DA} = 7.5 %	0.5	65	52 - 56
Kiyota et al. 2008	Air-pluviation	γ_{DA} = 10 %	1.0	100	40 - 50
Chiaro et al. 2012	Air-pluviation	γ_{SA} = 7.5 % (≈ γ_{DA}/2)	1.0	100	44 - 45

[a] e_i = initial specimen void ratio, [b] $\sigma'_{hc}/\sigma'_{vc}$ = 1.0 for test performed at a CSR = 0.147.

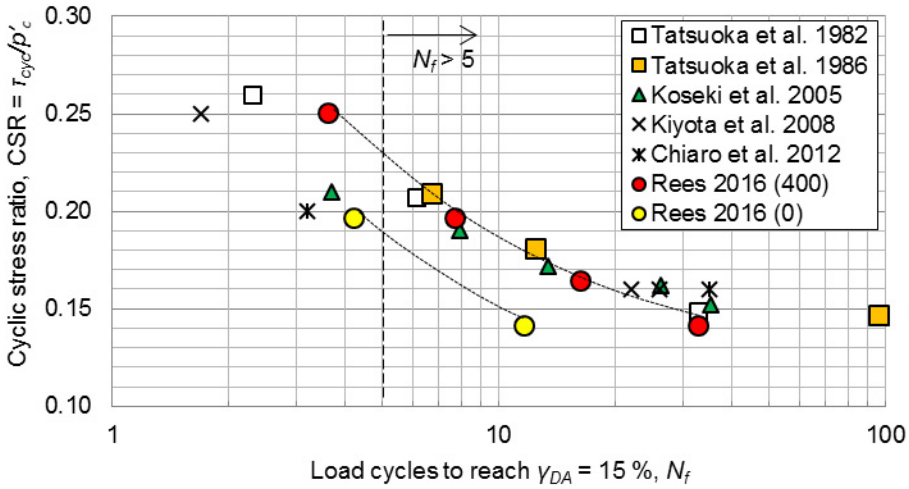

Figure 3. Cyclic data for Toyoura sand specimens tested in cyclic simple shear conditions.

Secondly, the cyclic resistance data for the Toyoura sand specimens with $N_{c,ps}$ = 400 compare well with the HC test data when N_f > 5. More specifically, the curve fitted to this study's data (for $N_{c,ps}$ = 400) locates to within 4 % of the Tatsuoka et al. 1986 data points, which is the most similar data set to this study (anisotropic consolidation, moist-tamping reconstitution). This observation suggests that, for Toyoura sand prepared to medium density, 400 cycles of pre-shearing will subsequently produce undrained cyclic simple shear response essentially equivalent to that obtained in the HC apparatus.

Finally, a significant amount of variation in the cyclic resistance data is observed when N_f < 5. It is however noted that all HC data in this region was obtained from air-pluviated specimens, and that a divergence in cyclic resistance has previously been reported between moist-tamped and air-pluviated specimens when N_f < 5 and D_r ≈ 50 % (Tatsuoka et al. 1982). In this previous study the moist-tamped specimens were shown to have larger cyclic resistances than air-pluviated specimens when N_f < 5, which is consistent with the trend observed in Figure 3.

3.4 Practical recommendations suggested from this study

The most encouraging observation discussed in this study is that application of drained cyclic pre-shearing using a relatively small stress ratio produces CRR values for Toyoura sand in an NGI-type CSS apparatus essentially equivalent to those derived from high-quality HC testing during previous liquefaction studies. This equivalence with the benchmark HC test data strongly suggests the primary effect of pre-shearing is to shift the overall test condition in the CSS apparatus closer to the idealised test model (through improved specimen-apparatus interfacing, minimisation of reconstitution effects, levelling out of stress concentrations etc.), as opposed to increasing the sand's inherent resistance to cyclic loading. Given this outcome, it is suggested the following steps are employed by laboratories when CSS tests are performed in an NGI-type apparatus on medium-dense (or looser) clean sands as part of detailed liquefaction assessments:

- At least 400 load cycles of drained cyclic pre-shearing should be applied to reconstituted specimens before undrained cyclic loading takes place; and,
- The drained pre-shearing stress ratio should be of the order of τ_{cyc}/σ'_{vc} ≈ 0.04 to 0.05, with the shear strain approximately limited to the elastic threshold of the material.

Note it is currently unclear what effect pre-shearing has on the CRR of intact and/or high-quality undisturbed specimens. Given that pre-shearing appears to improve the overall CSS test condition, it is suggested pre-shearing be used. A future study investigating the effect of pre-shearing on the CRR of undisturbed specimens would however prove practically useful for test laboratories. It is also noted the observed improvement in CRR values presented in this study is limited to clean sand prepared to 50 % D_r and pre-sheared using a stress ratio of $\tau_{cyc}/\sigma'_{vc} \approx 0.045$. It is currently unclear what improvement in CRR values may be obtained when soil density and/or pre-shear stress ratio is varied.

4 CONCLUSIONS

Ten undrained cyclic direct simple shear (CSS) tests were performed on reconstituted medium density Toyoura sand specimens in an NGI-type apparatus to assess the effect of drained cyclic pre-shearing on the undrained cyclic resistance of clean sand. Pre-shearing was performed at a cyclic stress ratio of $\tau_{cyc}/\sigma'_{vc} \approx 0.045$ while the effective vertical consolidation stress was held constant.

It was observed that application of 400 pre-shearing load cycles produced cyclic resistances in the CSS apparatus essentially equivalent to those of Toyoura specimens tested in the hollow cylinder apparatus. When pre-shearing was not employed, the cyclic resistance was found to be approximately 20 % lower. Additionally, it was observed that pre-shearing does not significantly change relative density, and that pre-shearing beyond 400 load cycles does not further increase the cyclic resistance by a significant amount. It is therefore recommended that drained cyclic pre-shearing be employed when testing clean sand specimens in a CSS apparatus for use in liquefaction analyses. Exclusion of this component in a CSS test may result in CRR estimates significantly lower than what would be considered representative of in-situ behaviour, potentially leading to unnecessary conservatism in engineering design when working with liquefiable soil deposits.

5 ACKNOWLEDGEMENTS

The author wishes to thank L'École des Ponts ParisTech for kindly providing the Toyoura sand used in the laboratory study, the management team at GDS Instruments for providing the time and resources to complete the laboratory study, and all at Tonkin + Taylor Ltd for their support in writing this paper.

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