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On the use of compliance correction for performing truly constant volume cyclic direct simple shear tests on sands

Sur l'utilisation de la correction de conformité pour la réalisation d'essais de cisaillement simple cyclique à volume vraiment constant sur les sables

M. Konstadinou*
Deltares, Delft, The Netherlands

A. Bezuijen
Ghent University, Ghent, Belgium

**maria.konstantinou@deltares.nl*

ABSTRACT: The cyclic undrained Direct Simple Shear (DSS) response of sand samples is predominantly influenced by the stiffness of the apparatus. Recent findings have shown that a stiffer apparatus results in a lower cyclic resistance response compared to a more flexible apparatus for which the number of cycles to liquefaction is higher. Consequently, the cyclic response of the sand samples is not only controlled by the soil behaviour itself but by the stiffness of the DSS device. High quality DSS test results on dense sand require a very stiff device that minimizes compliance to ensure truly constant volume (undrained) conditions. In this study, the device compliance is reduced to tolerated limits via actively correcting the vertical displacement response of the system during testing such that the height of the sample remains constant. Cyclic DSS tests on dense sand samples are performed and presented in this study for different compliance correction equations.

RÉSUMÉ: La réponse cyclique non drainée en cisaillement direct (DSS) d'échantillons de sable est principalement influencée par la rigidité de l'appareillage. Des découvertes récentes ont montré qu'un appareillage plus rigide entraîne une réponse de résistance cyclique inférieure par rapport à un appareillage plus flexible, pour lequel le nombre de cycles jusqu'à la liquéfaction est plus élevé. Par conséquent, la réponse cyclique des échantillons de sable n'est pas uniquement contrôlée par le comportement du sol lui-même, mais aussi par la rigidité du dispositif DSS. Pour obtenir des résultats de test DSS de haute qualité sur du sable dense, il est essentiel d'utiliser un dispositif très rigide qui minimise la conformité pour assurer des conditions vraiment constantes de volume (non drainées). Dans cette étude, la conformité de l'appareil est réduite à des limites tolérables en corrigeant activement la réponse de déplacement vertical du système pendant les essais, garantissant que la hauteur de l'échantillon reste constante. Des essais cycliques DSS sur des échantillons de sable dense sont réalisés et présentés dans cette étude en utilisant différentes équations de correction de conformité.

Keywords: Direct simple shear tests; apparatus stiffness; cyclic testing; dense sands.

1 INTRODUCTION

To mimic undrained behaviour, the DSS apparatus uses the conservation of volume by inhibiting any volume strain changes of the sample during shear. Following Dyvik et al. (1987), the change in vertical stress during shearing under constant height conditions, is assumed to be equal to the excess pore water pressure generation. However, the apparatus will have a finite stiffness. This means that a stress reduction, as will occur during cyclic loading, will lead to some volume change of the sample. Konstadinou et al. (2020), showed that the stiffness of the DSS apparatus is of major importance as it proved to control the cyclic behaviour of dense sand samples. ASTM D6528 states that for an undrained monotonic constant volume test the DSS device shall allow a sample change in height of less than 0.05%. To comply with this allowable limit, the DSS devices in use must be very stiff. To the authors' knowledge, however, most DSS devices in use today are unable to satisfy such high stiffness requirements. This paper presents a methodology for performing DSS tests that comply with the 0.05% criterion. Herein a series of cyclic DSS tests is performed for which the system compliance introduced during shearing is compensated by actively changing the vertical displacement response of the system to keep the height of the sample constant. Furthermore, to evaluate if truly constant volume conditions are achieved, the volume change of the samples during cyclic loading is measured.

2 MATERIAL & TESTING CONDITIONS

The tests were carried out in the geotechnical laboratory of Deltares in The Netherlands. For measuring volume changes of the samples during testing, the DSS apparatus is equipped with a water tank connected with a closed system to the inlet at the top of the sample. The water tank is placed on a precision weighing balance which continuously monitors the inflow/outflow of fluid in the water tank. Tests were performed on cylindrical samples having a diameter of 63 mm and a height at preparation of approximately 20 mm. A standard research sand, the Toyoura sand is used which has been extensively used in previous studies (e.g., Kiyota et al. 2008; Chiaro et al. 2012). All samples were prepared by the air pluviation method (Mulilis et al. 1977). The initial relative density of the samples is $D_{r,i} \approx 80\%$, and the samples were consolidated to 200 kPa starting from an initial stress state at preparation of 10 kPa. The samples were saturated by flushing carbon dioxide through the voids among the sand particles and by subsequently percolating de-aired water from the bottom to the top of the sample. The samples were saturated to allow measurement of volume change during consolidation and shearing. The volume change is determined from the amount of water that is expelled from or drawn into the sample. After saturation, the samples were consolidated to $\sigma_{vi}' = 200$ kPa. The samples were presheared (drained) at $\tau_{SA}/\sigma_{vi}' = 0.03$ for 400 cycles, where τ_{SA} is the single-amplitude cyclic shear stress, with a frequency of 1 Hz. Samples were presheared to mitigate sample inhomogeneity and to replicate the in-situ stress history of soils subjected to drained preshearing prior to the main design event. After a consolidation period of 1 hour, the samples were subjected to cyclic loading under undrained simple shear conditions at $\tau_{SA} = \pm 20$ kPa. Cyclic loading was applied by way of a sinusoidal shear at a frequency of 0.02 Hz. The samples in this study were laterally confined by means of a rigid metal ring stacks enclosing an unreinforced rubber membrane. Table 1 summarizes the testing conditions of all the tests reported in this study.

Table 1. Sample characteristics.

Test	CC	D_r (%)	N_f (-)	K_m (kPa/mm)
NC_1	NC	88	86	K_i =4,049
NC_2	NC	85	113	
NC_3	NC	86	74	
WC_A_1	A	89	29	‘infinite’
WC_B_1	B	88	51	12,727
WC_B_2	B	90	47	

Note: CC, Compliance Correction; NC, No Compliance correction; WC, With Compliance correction; D_r, relative density after consolidation; N_f, number of cycles required to develop single amplitude of shear strain, $\gamma_{SA} = 5\%$; K_i, apparatus stiffness, K_m, modified apparatus stiffness.

3 SYSTEM COMPLIANCE

Compliance tests were conducted on a 20 mm thick dummy aluminium sample, which was subjected to three loading - unloading vertical load loops within the stress range of interest in this study, close to the sample’s consolidation stress level of 200 kPa (compliance stress range: 10 – 300 kPa). In the years of operation of the DSS apparatus mobilized herein, several compliance tests were performed on aluminium samples. Figure 1(a) shows the upper and lower bound best fit lines to the compliance data from such tests which will be refer to in this paper as compliance “Correction A” and “Correction B” curves respectively and are described with a 4th degree polynomial equation. It should be noted that the compliance test on an aluminium sample performed prior to the start of the current test series agrees with the compliance “Correction A” data. The secant apparatus stiffness, K_i, as determined from the compliance “Correction A” curve at the consolidation stress level of 200 kPa is K_i = 4,049 kPa/mm.

To account for compliance, “Correction A” and “Correction B” equations have been implemented in the active height control loop of the apparatus. During shearing and for an applied vertical load, the LVDT vertical displacement response of the system is adjusted to compensate for the compliance displacement as derived via the employed correction equations. When no compliance correction is applied, the LVDT vertical displacement values are negligible as shown in Figure 1(b). Figures 1(c) & 1(d) plot the measured LVDT vertical displacement with the applied vertical displacement as calculated via the use of “Correction A” and “Correction B” compliance equations respectively. It should be noted that in Figure 1 a positive measured LVDT displacement corresponds to a movement in the opposite direction of displacement due to compliance. By employing compliance corrections, the stiffness of the apparatus is modified. The modified stiffness, K_m, is higher compared to the original apparatus stiffness (K_i = 4,049 kPa/mm, no compliance correction) and has a value of K_m = 12,727 kPa/mm for the compliance “Correction B” tests while in theory an ‘infinite’ apparatus stiffness is achieved for the compliance “Correction A” test.

4 TEST RESULTS

Figure 2 presents the development of volumetric strain, ε_v, with vertical stress ratio, $\Delta\sigma_v'/\sigma_{vi}'$, during shearing of the samples up to reaching failure. Note that in this figure, a positive volumetric strain corresponds to a volume reduction of the sample.

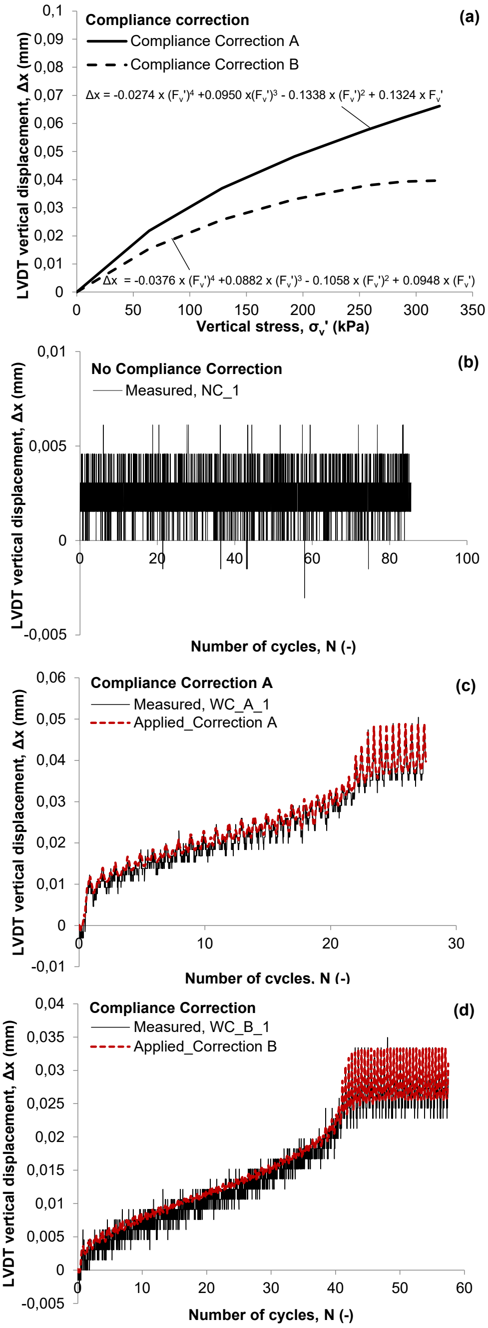

Figure 1. (a) Best fit compliance curves. Measured and applied LVDT vertical displacement as function of the number of loading cycles for tests with (b) no compliance correction, (c) compliance "Correction A" and (d) compliance "Correction B". The units in the compliance correction equations in Figure 1(a) are given in mm for the LVDT vertical displacement, Δx, and in kN for the vertical force, F_v'. The DSS sample diameter is 63 mm.

It is noteworthy that the sample for which no compliance correction is applied has a higher volumetric strain compared to the samples with compliance correction [Figure 2(a) cf., Figure 2(b) & 2(c)]. Using compliance "Correction A" and "Correction B" equations, the predicted volumetric strain distribution is also plotted against the experimental data in Figure 2. In overall, Figure 2 shows that only when compliance corrections are applied, the volumetric strain remains within the maximum tolerated change of ±0.05% as prescribed in ASTM D6528. In Figure 3 the number of cycles, N_f, required to develop a single-amplitude shear strain γ_{SA}=5% is plotted versus the modified apparatus stiffness, K_m, for the tests in this study performed with and without the use of compliance correction equations. As aforementioned, the influence of the apparatus stiffness on the cyclic response of dense Toyoura sand samples has been investigated by Konstadinou et al. (2020). To evaluate this influence, the stiffness of the apparatus has been altered via the use of spring rings attached to the apparatus. The test data reported in Konstadinou et al. (2020) are also shown in Figure 3. It is evident that the resistance to cyclic loading depends on the rigidity of the DSS apparatus. Particularly for the employed apparatus, the number of cycles required to reach γ_{SA} = 5% decreases by about 70% when the apparatus is tricked to operate at its stiffest mode ('infinite' stiffness). In practice, the data in Figure 3 indicate that past results of cyclic DSS tests, particularly those on dense sand samples, should be treated with caution if the apparatus stiffness has not been considered in the data interpretation.

5 CONCLUSIONS

The performance of truly constant volume cyclic direct simple shear tests can be achieved only when the compliance of the system within the height control measurement area is 'infinite'. This is practically impossible as the apparatus will have a finite stiffness. Two options are available to reduce the system's compliance to allowable limits. That is to use a DSS apparatus that: (i) meets the high stiffness requirements or (ii) controls the height of the sample alone and keeps it constant with high accuracy. Modifying the DSS devices in use today to allow for the above options can be costly or simply not feasible. An alternative option has been explored in this paper based on which the sample's volumetric strain is kept within tolerated limits by correcting the displacement during shearing to account for the system's compliance. This option is recommended to be applied to every cyclic DSS test, but it requires, however, an active height control system that reacts swiftly to changes in the vertical load. For a slower system, compromises must be made on the value of the applied loading frequency.

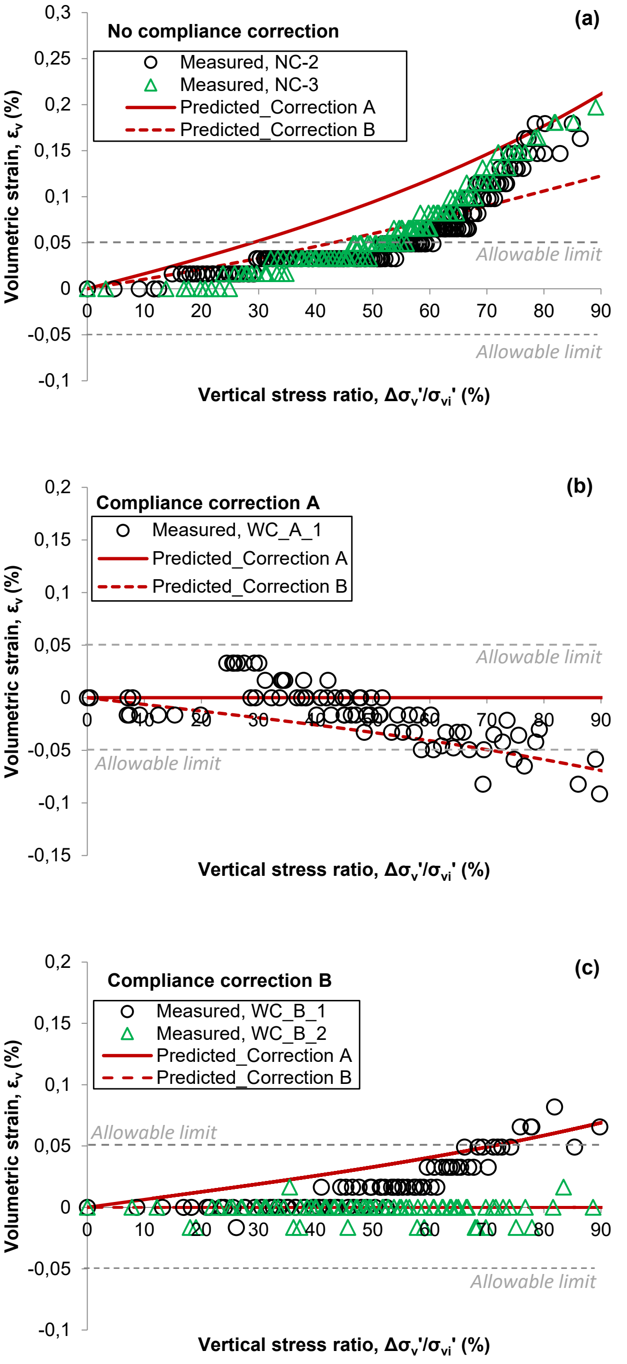

Figure 2. Measured and predicted volumetric strain, $\Delta\varepsilon_v$, against vertical stress ratio $\Delta\sigma_v'/\sigma_{vi}'$, for tests: (a) with no compliance correction (NS_1, NS_2 & NS_3), (b) with compliance correction A (WC_A_1) and (c) with compliance correction B (WC_B_1 & WC_B_2).

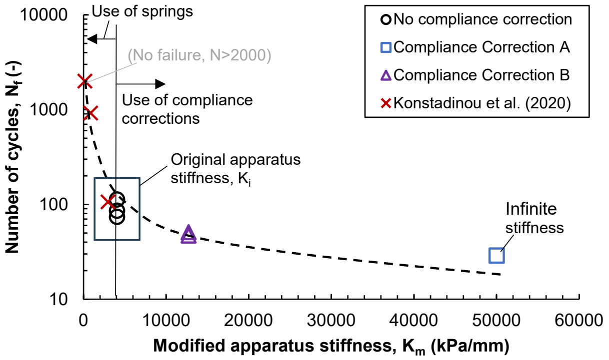

Figure 3. Relationship between number of cycles to develop a single amplitude of shear strain of γ_{SA} = 5 % and modified apparatus stiffness, K_m.

REFERENCES

ASTM D6528 (2017). Standard test method for consolidated undrained direct simple shear testing of fine grain soils. *ASTM International*, West Conshohocken, PA, www. astm.org.

Chiaro, G., Koseki, J., and Sato, T. (2012). Effects of initial static shear on liquefaction and large deformation properties of loose saturated Toyoura sand in undrained cyclic torsional shear tests. *Soils Found.*, Vol. 52(3), pp. 498 – 510. https://doi.org/10.1016/j.sandf.2012.05.008.

Dyvik, R., Berre, T., Lacasse, S., and Raadim, B. (1987). Comparison of truly undrained and constant volume direct simple shear tests. *Géotechnique*, Vol. 37(1), pp. 3-10. https://doi.org/10.1680/geot.1987.37.1.3.

Kiyota, T., Sato, T., Koseki, J., and Abadimasand, D. (2008). Behaviour of liquefied sands under extremely large strain levels in cyclic torsional shear tests. *Soils Found.*, Vol. 48(5), pp. 727 – 739. https://doi.org/10.3208/sandf.48.727.

Konstadinou, M., Bezuijen, A., Greeuw, G., Zwanenburg, C., Van Essen, H.M and Voogt, L. (2020). The influence of apparatus stiffness on the results of cyclic direct simple shear tests on dense sand. *Geotechnical Testing Journal*, Vol. 44(5), pp. 1501-1525. https://doi.org/10.1520/GTJ20190471.

Mulilis, J. P., Arulanandan, K., Mitchell, J. K., Chan, C. K., and Seed, H. B. (1977). Effects of sample preparation on sand liquefaction. *J. Geotechnical Eng. Division ASCE*, 103(GT2), pp. 91 – 108. https://doi.org/10.1061/ajgeb6.0000387.

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