Evaluation of DSS test results on granular soils based on T_xSS results

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ABSTRACT
Although direct simple shear (DSS) tests represent quite well the cyclic shear mode of the soil under seismic loading conditions, one of its main flaws is its lack to monitor the change of the confining stress of the tested specimen during shearing. Accordingly, the complete stress state of the soil sample is typically not defined, and in turn, this limits the use of the DSS test results, in particular, for the calibration of soil constitutive models. In this paper, the new combined triaxial simple shear (T_xSS) apparatus is employed to evaluate the DSS test results on granular soils. The T_xSS system consists of a direct simple shear system incorporated in a typical triaxial cell for the purpose of applying and monitoring the lateral confinement as well as the pore water pressure generation during strain-controlled loading conditions. Parallel monotonic and cyclic T_xSS tests on different saturated Baie-Saint-Paul sand specimens with (DSS) and without (T_xSS) stacks of annular plates at different confining pressures and draining conditions were conducted to evaluate the performance of the DSS results against the results obtained from the T_xSS. The results corroborate the practical recommendations that stress the use of DSS to investigate the shearing behavior of sands at small strains, but less so for evaluating large-strain behavior.

RÉSUMÉ
Bien que l'essai de cisaillement simple (DSS) représente relativement bien le mode de cisaillement cyclique du sol dans des conditions de chargement sismique, un de ses principaux défauts est son incapacité à suivre l'évolution de la contrainte de confinement de l'échantillon testé pendant le cisaillement. En conséquence, l'état de contrainte complet de l'échantillon de sol n'est généralement pas défini, ce qui limite l'utilisation des résultats des essais DSS, en particulier, pour l'étalonnage des modèles de comportement du sol. Dans cet article, le nouvel appareil de cisaillement simple triaxial (T_xSS) combiné est utilisé pour évaluer les résultats des essais DSS sur les sols granulaires. Le système T_xSS compose d'un système de cisaillement simple incorporé dans une cellule triaxiale dans le but d'appliquer et de suivre le confinement latéral aussi bien que la génération de la pression de l'eau interstitielle dans les conditions de chargement contrôlée. Des essais T_xSS monotones et cycliques ont été menés sur un sable de Baie-Saint-Paul en parallèle avec des essais (DSS) à différentes pressions de confinement et conditions de drainage pour comparer les résultats des essais DSS avec ceux obtenus à partir de la T_xSS. Les résultats corroborent les recommandations pratiques qui mettent l'accent sur l'utilisation de DSS pour étudier le comportement de cisaillement des sables aux petites déformations, mais moins pour évaluer le comportement à grandes déformations.

1 INTRODUCTION

Direct simple shear (DSS) apparatuses are often desirable as they can impose a state of plane strain and allow a smooth and continuous rotation of the principal stress directions during shearing; a condition that appears to more realistically approximate the stress-strain state to which soils experience in many practical geotechnical situations. These situations include soils in a slope failure zone, adjacent to a friction pile, and beneath the foundation of an offshore platform. In other words, the simple shear deformation or the failure pattern observed in the DSS test is consistent with those encountered in the field; such as earthquake ground deformation due to vertical or nearly vertical S-wave propagation (Makiuchi et al. 1983; Budhu and Britto 1987; Dyvik et al. 1987; Boulanger et al. 1993; Duku et al. 2007; Sadrekarimi and Olson 2009; Dabeet et al. 2012).

Two DSS apparatuses are in common use in the modern geotechnical community: the Cambridge University (Roscoe 1953) and the Norwegian Geotechnical Institute (NGI) (Bjerrum and Landva 1966). In both cases, the soil specimen is confined laterally within rigid metallic wall or using a wire-reinforced rubber membrane to achieve zero-lateral strain conditions during shearing. Merits and limitations of the DSS compared to other conventional laboratory tests have been detailed and discussed elsewhere, and the interested reader is referred to (e.g., La Rochelle 1981; Saada et al. 1982; Vucetic and Lacasse 1982; Makiuchi et al. 1983; Bhatia et al. 1985; Airey and Wood 1987; Budhu and Britto 1987; Boulanger et al. 1993).

One of the principle deficiencies of the DSS devices is their flaw to monitor the change of the lateral stress acting on the reinforced membrane wall (i.e., the confining stress of the tested soil specimen) during shearing. Accordingly, the complete stress state of the sample cannot be directly calculated. In fact, the boundary conditions in the apparatus don't permit the soil sample to respond as a single element; an issue that limits the usefulness of this test method for developing a proper understanding of fundamental stress-strain soil behavior, and Impedes its further use in the development and validation of constitutive soil models (e.g., Wood et al. 1979; Budhu 1985; Dabeet et al. 2012).

In an attempt to minimize the difficulties and errors associated with the DSS as well as other conventional techniques, and to obtain high quality experimental test data on the static and dynamic characteristics of soil samples in a triaxial condition, Chekired et al. (2015) designed and constructed a new combined triaxial simple shear (T_xSS) apparatus. The T_xSS system consists of a simple shear apparatus incorporated in a triaxial cell. The T_xSS has the ability to consolidate a soil specimen under drained conditions to a desirable confining pressure, and then shear it under either drained or undrained conditions. It provides the opportunity to apply back pressure to ensure full saturation of the specimen and the direct measurement of the pore water pressure during the undrained shear test. It also has the ability to rotate principle stresses of the tested specimen during shearing. Moreover, the T_xSS provides the opportunity to utilize a soil sample with a height large enough to develop a well-defined failure zone. The T_xSS can be simply reduced to the DSS if the soil sample, prepared in a membrane-enclosed space, is surrounded by stacks of annular plates/rings and a zero-confining pressure is applied.

In this paper, the authors would like to examine the performance of the DSS results against the results obtained from the T_xSS apparatus and to evaluate the effects of different factors such as the sample size and shearing rate on the measured data on both tests. To this end, parallel monotonic and cyclic T_xSS tests on different saturated Baie-Saint-Paul sand specimens with (DSS) and without (T_xSS) stacks of annular plates at different confining pressures and draining conditions were conducted. The results are compared and discussed, and the primary findings are summarized as conclusions

2 EXPERIMENTAL DSS AND T_XSS TESTS

The new combined triaxial simple shear (T_xSS) apparatus is employed in this paper to evaluate the DSS test results on Baie-Saint-Paul sand having the physical properties and the grain-size distribution shown, respectively in Table 1 and Fig. 1. The wet tamped preparation method was utilized to prepare reconstituted soil specimens in a rubber membrane as shown in Fig. 2. The soil specimen was 76 mm in diameter and 25.8 or 40 mm height. Moist sand was placed in three layers and every layer is compacted to a 56% initial relative density. As mentioned earlier, the T_xSS can be simply reduced to the DSS if the soil sample, prepared in a membrane-enclosed space, is surrounded by stacks of annular plates (rings) as those shown in Fig. 3c. Parallel monotonic and cyclic T_xSS tests on different saturated Baie-Saint-Paul sand specimens with (DSS) and without (T_xSS) the annular rings at different draining conditions were conducted. The specimen is located between relatively rigid bottom and top caps that contain fine porous stones provide a "frictional" surface while allowing for drainage into the porous stones. After saturation, with a Skempton's B value greater than 0.97, Bais-Saint-Paul sand specimens, tested in the T_xSS condition, were consolidated under an effective confining stress of 75 kPa. Baie-Saint-Paul sand specimen preparations in the T_xSS and DSS tests are shown in Figs 2 and 3, respectively. Before the application of the monotonic shearing (up to shear strain of 20%) at the top cap, the soil specimen tested in either the DSS or TxSS was subjected to a cyclic small shear strain amplitude (on the order of ±0.44%) for 20 cycles without drainage. The pore water pressure, which built up slightly during the application of the strain cycles, was released after the twentieth cycle. Some time was allowed for the sample to reach an equilibrium state before another 20 strain cycles of the same amplitude was applied. The observed responses of the tested soils in the DSS and T_xSS tests are compared as well as the effect of some parameters such as the shear rate and the specimen size in both monotonic and cyclic tests is addressed in the following sections.

Table 1: Physical properties of Baie-Saint-Paul sand.

Soil properties	**Baie-Saint-Paul sand**
G_s	2.78
I_d %	56
e_{max}.	0.91
e_{min}.	0.598
e	0.7375
ρ_{max} (Kg/m^3)	1745.4
ρ_{min} (Kg/m^3)	1457.4
ρ (Kg/m^3)	1600
C_u	2.25
C_c	1
D_{50}	0.15

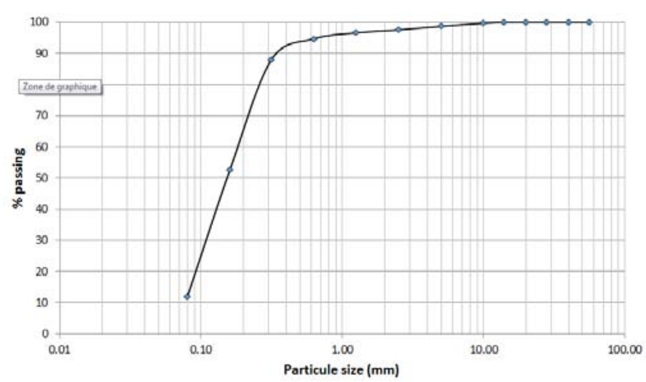

Figure 1. Grain-size distribution of Baie-Saint-Paul sand.

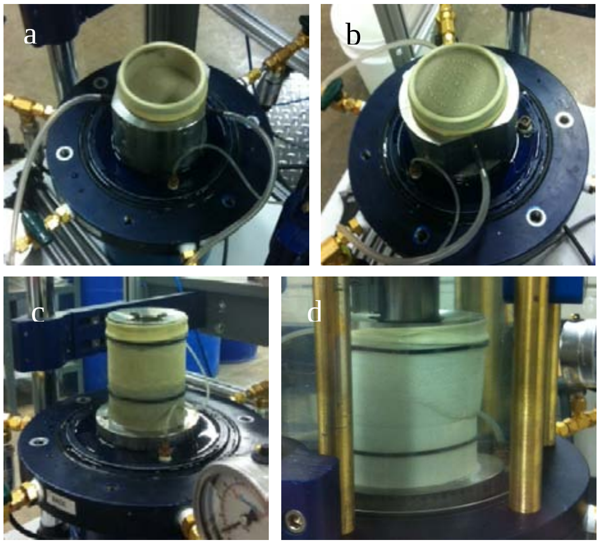

Figure 2. Soil specimen preparation in the T_xSS test.

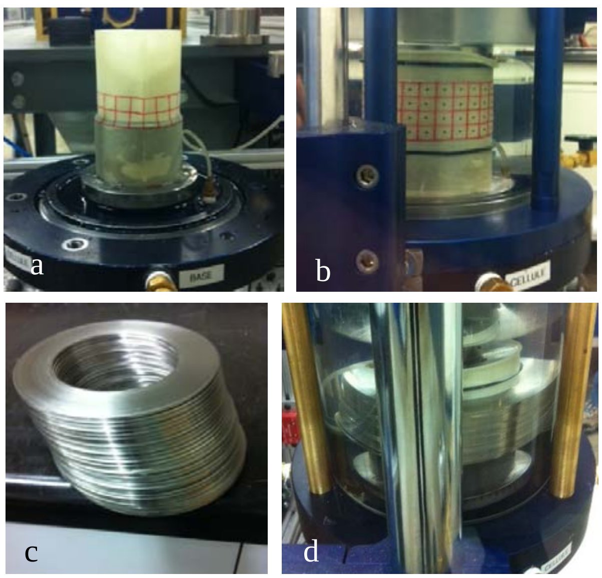

Figure 3. Baie-Saint-Paul sand specimen preparation in: (a), (b) T_xSS; (c), (d) DSS test.

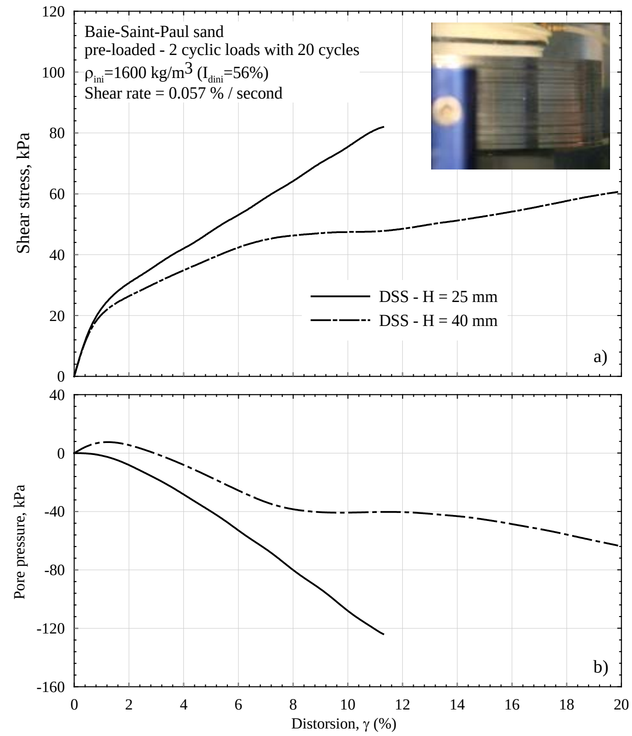

Figure 4. Typical results of monotonic DSS tests on Bais-Saint-Paul sand specimens: (a) shear stress-shear strain curve and (b) excess pore pressure -shear strain curve.

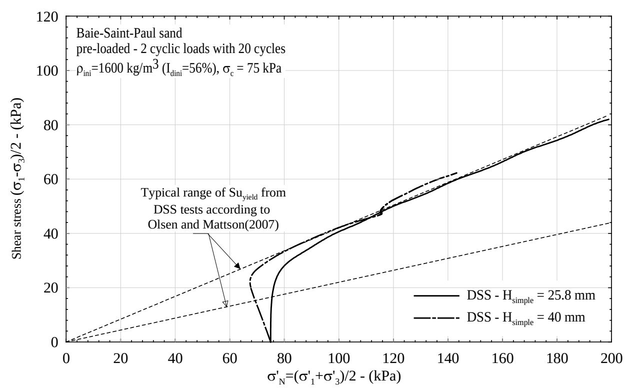

Figure 5. Stress paths of the two monotonic DSS tests on Bais-Saint-Paul sand specimens.

2.1 Monotonic loading DSS and T_xSS test results

In the DSS test, two Bais-Saint-Paul sand specimens were tested with the same diameter and different heights of 25.8 and 40 mm, and the shear strain is monotonically applied at the top cap at the same shear rate of 0.057%/second after preloading with the two cyclic patterns explained above. Representative shear stress-shear strain and pore pressure-shear distortion curves are shown, respectively in Figs. 4a and 4b. As typically observed from Fig. 4a, a rapid increase in the shear stress at relatively small shear strains is observed. This is followed by a gradual increase in shear stress with further development of shear strain. The results suggest that the shear stress as well as the excess pore pressure generally increase with the sample height.

An important point to be noted from Fig. 4a is that the shear stress development during shearing up to a relatively low shear strain of 0.8% is not significantly influenced by the sample size.

Stress path of the higher sample (H_{sample} = 40 mm) shown in Fig. 6 indicate an initially significant contractive behavior (i.e. decrease in vertical effective stress) followed by dilative behavior (i.e increase in vertical effective stress) which is the typically observed behavior for loose to medium loose sands. For the short sample (H_{sample} = 25.8 mm), the dilative behavior is observed for the whole range of the investigated shear strains of 0% - 20%. Moreover, the measured yield strengths of the two tested soil samples fall in the range provided by Olsen and Mattson (2008) based on a database of 386 laboratory triaxial compression, direct simple shear, rotational shear, and triaxial extension test results.

Typical results of four monotonic drained and undrained T_xSS tests on Bais-Saint-Paul sand specimens with I_d of 56% consolidated at a 75 kPa confining pressure with different sample heights of 25.8 and 40 mm are shown in Figs. 6a-c. In Fig. 6, the shear stress, the excess pore pressure, and the vertical deformation are plotted against the shear distortion. Similar to DSS test results, all the T_xSS results plotted in Fig. 6a show rapid increase in the shear stress at relatively small shear strains and the shear stress (Fig. 6a) as well as excess pore pressure (Fig. 6b) developed during shearing up to a relatively low shear strain of 0.8% are not significantly influenced by the sample size, shear rate, and draining condition. Excess pore pressure versus shear strain plot shown in Fig. 6b suggests a contractive behavior for the range of shear strains up to 3.5% in the higher sample (40 mm). Beyond this limit, the soil sample shows a dilative behavior. On the other hand, for the short sample (25.8 mm), the dilative behavior is observed for the whole range of the investigated shear strains of 0% - 20%. Stress paths shown in Fig. 7 indicate that the measured yield strengths of the four tested soil samples fall in the range provided by Olsen and Mattson (2008) in compression triaxial test.

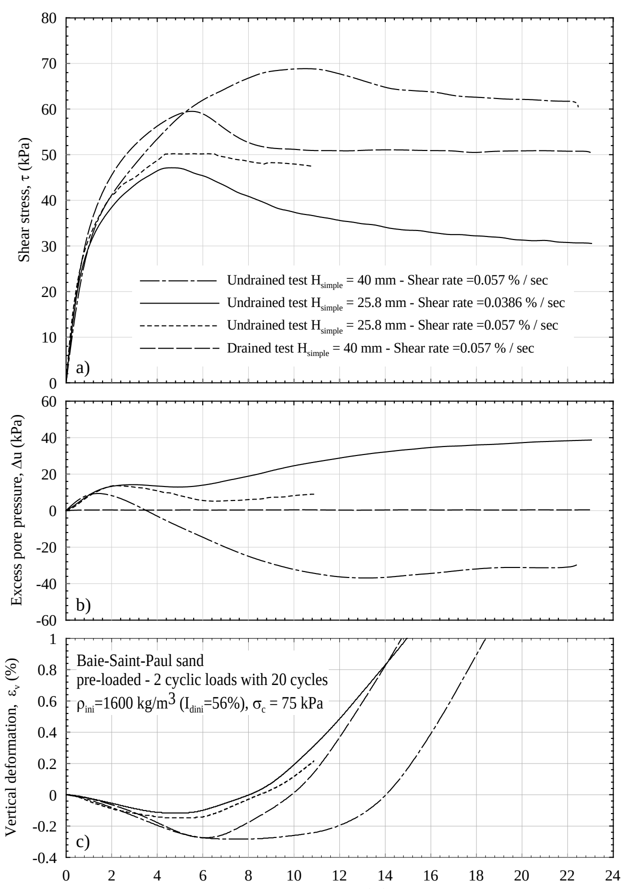

Figure 6. Typical results of monotonic T_xSS tests on Bais-Saint-Paul sand specimens: (a) shear stress-shear strain curve; (b) excess pore pressure-shear strain curve; and (c) vertical deformation-shear strain curve.

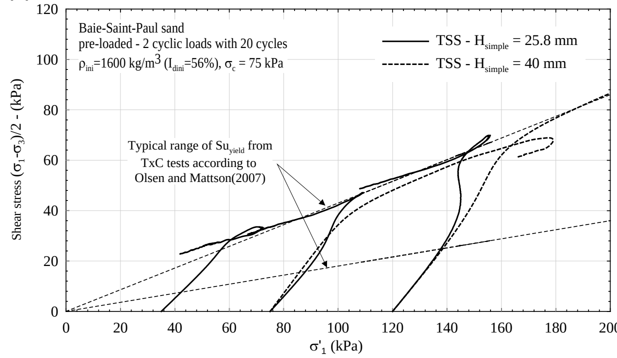

Figure 7. Stress paths of the monotonic T_xSS tests on Bais-Saint-Paul sand specimens.

2.2 Cyclic loading DSS and T_xSS test results

Typical results of cyclic DSS tests on Bais-Saint-Paul sand (I_d = 56%) are compared to those obtained from T_xSS tests in Figs. 8-10 in terms of cyclic stress ration (CSR) and excess pore pressure (r_u). Where CSR is defined as the amplitude of the cyclic shear stress (τ_{cyc}) divided by the initial effective confining stress (σ'_c), while r_u is defined as the ratio of the measured pore pressure to the initial confining pressure. Figures 8 and 9 belong to tests with a specimen height of 25.8 mm, while Fig. 10 belongs to tests with a specimen height of 40 mm.

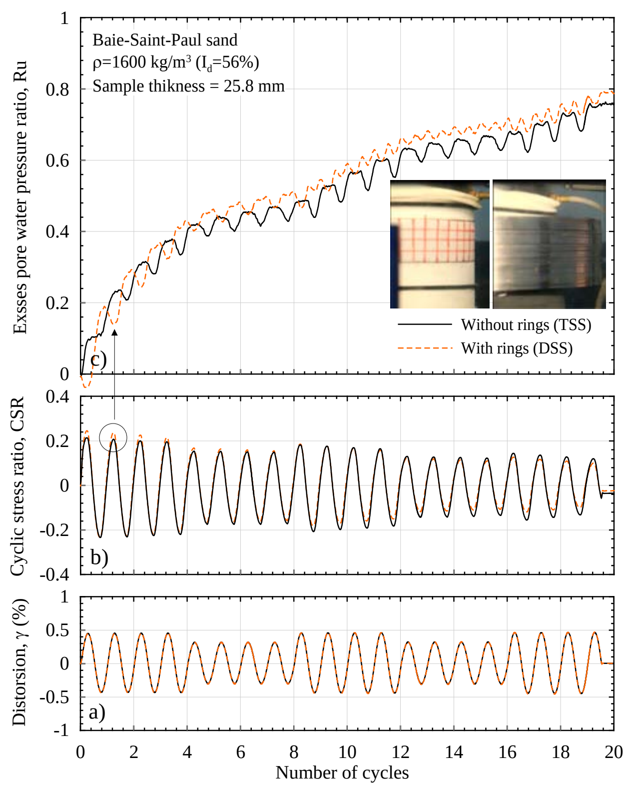

Figure 8. Typical results of cyclic DSS and T_xSS tests on Bais-Saint-Paul sand specimens with a 25-mm height.

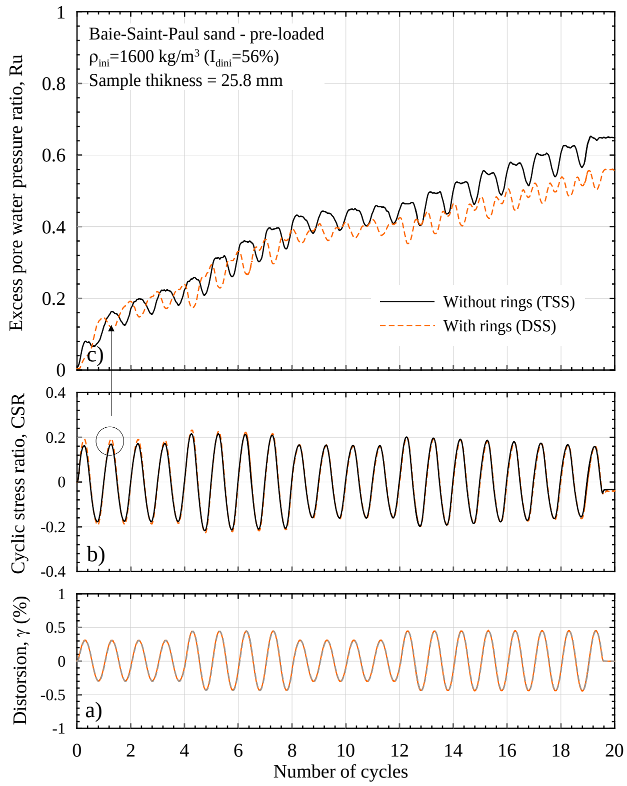

Figure 9. Typical results of cyclic DSS and T_xSS tests on Bais-Saint-Paul sand specimens with a 25-mm height.

The difference between Fig. 8 and Fig. 9 is the sequence of shear strain history considered. It should be noted that the maximum applied shear strain to soil specimen in all tests presented in Figs. 8-10 is 0.44%. Figures 8-10 indicates that irrespective of the sample height and the sequence of shear strain history considered, using the DSS test condition produces CSR and r_u values that is in accordance with those obtained from the T_xSS condition in the strain range considered in the tests ($\gamma \leq 0.44\%$).

Comparison between the DSS and T_xSS test results are also presented using the energy-based concept for evaluating liquefaction and residual excess pore pressure generation first introduced in the 1970s as an alternative to stress-based procedures (e.g., Nemat-Nasser and Shokooh 1979). Energy-based pore pressure models typically relate the ratio of excess pore pressure (r_u) generated during shearing to normalized unit energy, W_s that can be defined as the energy dissipated per unit volume of soil divided by the initial effective confining pressure (Polito et al. 2013). Where, the dissipated energy per unit volume for a soil sample in cyclic loading can be determined by integrating area bound by stress–strain hysteresis loops as suggested by Green et al. (2000) and schematically plotted in Fig. 11.

Figure 11 show a comparison between the predicted excess pore pressure ratios for the DSS and T_xSS on Bais-Saint-Paul sand specimens with heights of 25.8 mm and 40 mm using the energy-based concept following the work of Green et al. (2000) and Polito et al. (2013). Although the estimated pore pressure ration from the DSS

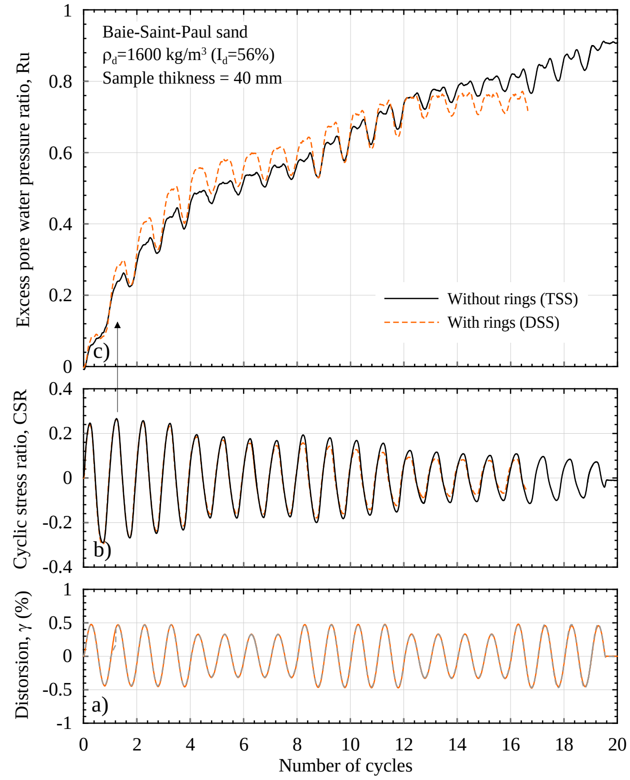

Figure 10. Typical results of cyclic DSS and T_xSS tests on Bais-Saint-Paul sand specimens with a 40-mm height.

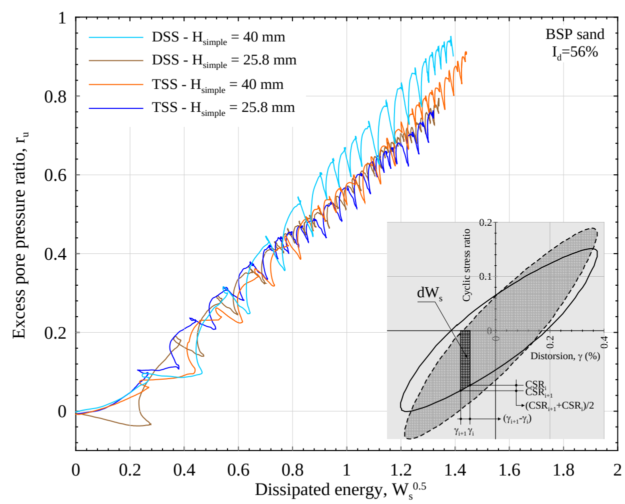

Figure 11. Comparison of predicted excess pore pressure ratios for DSS and T_xSS on Bais-Saint-Paul sand specimens.

test on a 40-mm sample height is relatively high approaching the end of the test, the DSS and the T_xSS give identical excess pore pressure curve irrespective to the sample height.

3 SUMMARY AND CONCLUSIONS

In this study, parallel monotonic and cyclic T_xSS tests on different saturated Baie-Saint-Paul sand specimens with (DSS) and without (T_xSS) stacks of annular plates at different confining pressures and draining conditions were conducted to evaluate the performance of the DSS results against the results obtained from the T_xSS. Although the conducted tests as well as the tested material considered in this study is limited, a number of useful findings have emerged:

1. The results of both monotonic DSS and T_xSS test conditions suggest that the shear stress as well as the excess pore pressure generally increase with the tested sample height. However, the measured shear stress during shearing up to a relatively low shear strain of 0.8% is not significantly influenced by the sample size. Moreover, the measured yield strengths of the tested soil samples with different heights fall in the range provided by Olsen and Mattson (2008).
2. Unlike the DSS results that show difference in the contraction/dilation sand behavior when samples with different heights were considered, the T_xSS results show similar contraction/dilation sand behavior irrespective of the sample heights.
3. Irrespective of the sample height and the sequence of shear strain history considered, using the cyclic DSS test condition produces CSR and r_u values that is in accordance with those obtained from the T_xSS condition in the strain range considered in the tests ($\gamma = 0.4\%$).
4. The estimated excess pore pressure ratios using the energy-based concept for the DSS test condition are identical to those from the T_xSS test condition irrespective to the sample height.

These results especially the latter two findings corroborates (supports) the practical recommendations that stress the use of DSS to investigate the shearing behavior of sands at small strains, but less so for evaluating large-strain sand behavior.

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