Assessment of the effect of specimen size and confinement method on the results of simple shear test

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ABSTRACT
Direct simple shear test has been widely used in geotechnical engineering due to its simplicity and reliability in evaluating soil characteristics under both monotonic and dynamic loading conditions. Different recommendations have been also provided with respect to the size and the confinement method of the tested soil specimens. However, a conclusive opinion on their effects on the shear strength, the generated pore pressure as well as the stress path of the tested soil has not yet been formed among practitioners and geotechnical engineers. Therefore, the prime objective of this paper is to assess the effect of the specimen size and the adopted confinement methods on the results of simple shear tests under both monotonic and dynamic loading. To this end, a series of monotonic and cyclic simple shear tests were performed using the recently developed combined Triaxial Simple Shear (T_xSS) apparatus (Chekired et al. 2015) on two sensitive Sea Champlain clays from eastern Canada. Soil specimens with different height-to-diameter ratios were tested in the T_xSS apparatus adopting different confinement methods (i.e., a reinforced and unreinforced membrane). The results of this study would be a valuable contribution to the ongoing global effort towards a more precise soil characterization at laboratory.
RÉSUMÉ
L'essai de cisaillement direct simple a été largement utilisé en génie géotechnique pour sa simplicité et sa fiabilité dans l'évaluation des caractéristiques du sol dans des conditions de charge monotone et dynamique. Différentes recommandations ont également été fournies en ce qui concerne la taille et la méthode de confinement des échantillons de sol testés. Cependant, une opinion concluante sur leurs effets sur la résistance au cisaillement, la pression interstitielle générée ainsi que le cheminement de contrainte du sol testé n'a pas encore été formée chez les praticiens et les ingénieurs en géotechnique. Par conséquent, l'objectif principal de cet article est d'évaluer l'effet de la taille de l'échantillon et des méthodes de confinement sur les résultats d'essais de cisaillement simples sous chargement monotone et dynamique. À cette fin, une série d'essais de cisaillement simple monotone et cyclique ont été réalisés à l'aide de l'appareil combiné Triaxial Simple Shear (T_xSS) récemment développé (Chekired et al., 2015) sur deux argiles sensibles de Champlain de l'est du Canada. Des échantillons de sol ayant différents rapports hauteur sur diamètre ont été testés dans l'appareil T_xSS en utilisant différentes méthodes de confinement (c'est-à-dire une membrane renforcée et non renforcée). Les résultats de cette étude constitueraient une contribution précieuse à l'effort global en cours pour une caractérisation plus précise des sols en laboratoire.

1 INTRODUCTION

Direct simple shear test is one of the most used tests in geotechnical engineering. It was developed by Norway Geotechnical Institute (Bjerrrum and Landva, 1966) to reproduce in laboratory the strain conditions experienced in the field such as those generated from earthquake loading (Terzaghi et al, 1996) as well as progressive landslides observed in Eastern Canadian and Scandinavian sensitive clays (Locat et al, 2011). However, despite its advantages, the direct simple shear test has well-known shortcomings. Budhu (1984) observed that the direct simple shear device imposes nonuniform stress and due to the rotation of the stress state, the failure is initiated in vertical planes. The measurement of the pore water pressure during the simples shear test has been a subject of controversial research. According to Bjerrum and Landva (1966), Dyvik et al, (1987) the change in a vertical stress required to maintain the constant height of the sample is equivalent to the pore pressure generated in fully undrained constant load test. On other hand, based on experimental and numerical results, Saada et al, (1983) showed that the change in vertical stress is not equal to the pore pressure generated during the test and criticized severely the use of this assumption.

As an alternative, a new apparatus called T_xSS (Triaxial simple shear) has been recently developed by Research Institute of Hydro-Quebec and geotechnical laboratory at the University de Sherbrooke for a better understanding of the strain-strain behavior and pore pressure generation under monotonic and dynamic loadings. As described by Chekired et al (2015), the T_xSS test is carried out on a cylindrical soil sample with a diameter around 62 mm and varying diameter/height ratios. The specimen is fitted between two rigid top and base caps. Rubber and reinforced membranes or annular rings can be used to encase the soil specimen. The saturation and the consolidation system are the same as those in standard triaxial apparatus: a triaxial chamber is used to apply a confining and back pressure. The T_xSS is equipped also with vertical axe that allows applying a vertical loading and thus reproduces in-situ stress conditions.

Table 1: Geotechnical properties of the tested clays.

Clay	Depth (m)	W_n	W_{Lc}	W_p	I_p	I_L	%<2μm	D_r	σ'_p
Saint-Adelphe	5	61	51	21	21	1.9	66	2.79	100
Blainville	2	75	60	27	33	1.5	70	2.79	-

The shear loading is applied by imposing a displacement at the top cap of the specimen using a shear ram. The shear ram is connected to an electromagnetic shaker mounted in a horizontal table. The shaker can apply a monotonic loading as well as regular or irregular dynamic loadings to soil specimens. The acquisition system is composed of high sensibility transducers of displacement (0.07 nm) which allow to perform a test with a large range of strain (from 0.001 % to 10 %) and consequently the T_xSS can be used to examine both small (Chehat et al, 2018) and large (Karray et al. 2016) strain soil behavior.

In this context, standardizing of the T_xSS test is necessary to have some accurate results that can reproduce the desired conditions. For that reason, a literature review and an experimental program have been carried out to study the effect of a confinement method and the specimen size on the results of the T_xSS tests.

The effect of specimen size has been investigated by several authors. Vucetic and Lacasse (1982) performed a monotonic direct simple shear test on clayey soil with different Height/Diameter (H/D ranging between 0.32 and 0.14) ratio. They conclude that before the peak there is no effect of H/D ratio, however at large deformation, a slight divergence was observed in the stress-strain and pore pressure-strain curves. Carrol (1979) showed that the smaller diameter specimens have more monotonic and cyclic resistance to shear strain than the larger specimens, and K_o values is directly proportional to the sample height. Hussien et al (2015) perform DSS test with different Heights and they conclude that the shear stress as well as the pore pressure generally increase with the height of the sample. Chang et al (2016) performed a numerical experiment with distinct element modeling (DEM) in order to evaluate the size and boundary effect on DSS conditions. They conclude that the consistent shear strength can be obtained when the ratio of the sample height to the maximum particle size H/d_{max} is greater than 7 regardless of the value of H/D. Amer et al, (1987) studied the effect of specimen size on dynamic properties of soil. They observed that the shear modulus and damping ratio of dry sand at low strains decrease with the increase of D/H ratio. The same observations have been made by Kovacs and Leo (1981). Amer et al (1987), based on an experimental result on dry Ottawa sand, concluded that a specimen with diameter 20.32 cm and 2.54 height was the minimum specimen size in which the specimen is not affected by the its size. The American Society of Testing and Materials (ASTM) suggest in its standard D6528-17 for the undrained DSS test of fine grain soil that the minimum specimen diameter shall be 45 mm, the minimum height diameter shall be 12 mm and the ratio H/D shall not exceed 0.4. On the other hand, the confinement method has also been subjected to several investigations. McGuire (2011) compared the results of DSS tests with wire reinforced membrane and with Teflon coated stacked rings. He concluded that the peak shear strength was approximately equal for both methods. The same conclusion has been made by Grognet (2011). However, McGuire (2011) observed that there was a clear trend to more strain-softening behavior with wire reinforced membrane than stacked rings. Hussien et al (2015) performed cyclic DSS tests with a stacked rings and rubber membrane on Baie Saint Paul sand and they observed that there is no significant difference in excess pore pressure and cyclic stress ratio between these two confinement methods. In fact, it seems that the effects of specimen size and confinement methods on the behavior of tested soil are not yet clear and more experimental work is required to define the most proper specimen size and confinement methods in the T_xSS tests to reproduce as close as possible the field conditions.

2 SOIL DESCRIPTION

Two sensitive Eastern Canada clays are used is this study: Saint-Adelphe clay and Blainville clay. Table 1 present the main geotechnical properties of these clays.

2.1 Blainville clay

Blainville is a municipality located about 40 km in the North West of Montreal. The samples have been sampled by Ministère de Transport, de la Mobilité durable et Électrification des Transports using Shelby sampler (ASTM-D-1587). The samples used were obtained from 2 m depth with fine content around 70 %, water content 75 %, plastic index 33 % and liquid index 1.5.

2.2 Saint-Adelphe clay

Saint Adelphe is located near Trois-Rieveres City. The site was investigated after the landslide triggered by Saguenay earthquake 1988 (Lefebvre et al, 1992), (L'Ecuyer, 1998). Saint-Adelphe clay is a part of Sea Champlain clays. The samples were sampled by using Sherbrooke Sampler (Lefebvre and Poulin, 1979). The samples used in this study were obtained from 5 m depth. The clay is an overconsolidated clay with a liquidity index 1.9 and plastic index 21 %. The sensitivity measured with Swedish cone is 85 which classify this clay as quick clay (CGS,2006, Errata, 2013).

3 EXPERIMENTAL PROGRAM

The experimental program is composed of nine T_xSS tests. Table 2 present the conditions for each test. Five monotonic tests have been carried out in T_xSS apparatus on Blainville clay with the objective to study the effect of the change of the height of the samples and the confinement method. Tests N°1 and N°2 have been carried out with samples of 15 mm height and tests N°3 and N°4 with samples of 19 mm height and test N°5 with samples of 25 mm height.

Table 2 : Summary of T_xSS tests.

Test N°	Clay	Type of test	H (mm)	D (mm)	Confinement	σ'_{vc} (kPa)
1	Blainville	Monotonic	15	62	RM	25
2	Blainville	Monotonic	15	62	UM	25
3	Blainville	Monotonic	19	62	UM	25
4	Blainville	Monotonic	19	62	RM	25
5	Blainville	Monotonic	25	62	UM	25
6	Saint-Adelphe	Cyclic	19	62	RM	150
7	Saint-Adelphe	Cyclic	19	62	UM	150
8	Saint-Adelphe	Cyclic	25	62	RM	150
9	Saint-Adelphe	Cyclic	25	62	UM	150

RM: Reinforced membrane, UN: Unreinforced membrane

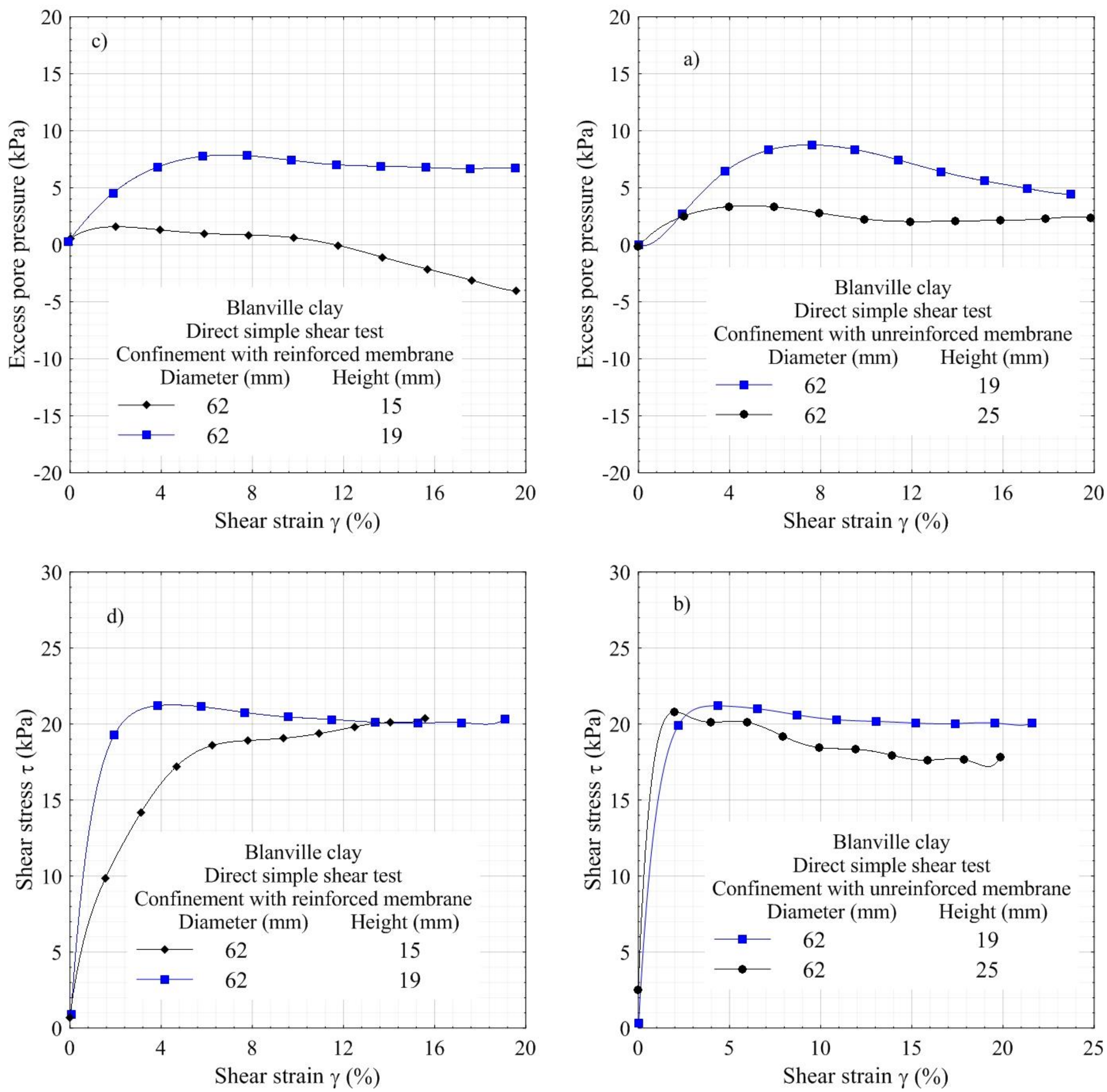

Figure 1 : Influence of the height of the specimen on the results of monotonic tests.

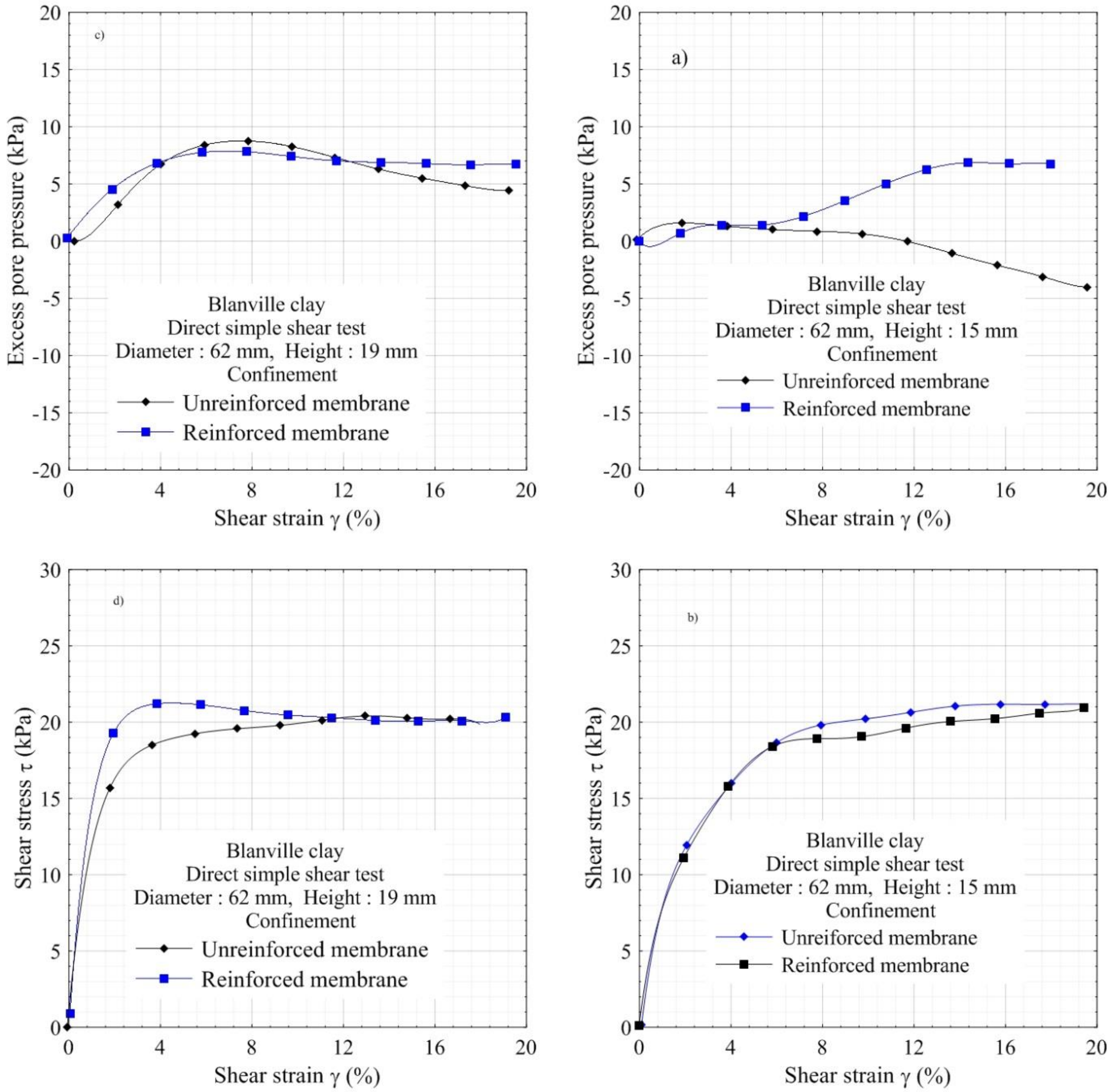

Figure 2 : Influence of the confinement method on the results of monotonic tests.

As shown in Table2, the first five monotonic T_xSS tests have been performed on Blainville clay having different heights. The reinforced membrane has been used in tests N°1 and N°4 and the unreinforced membrane have been used in tests N°2, N°3 and N°5. Four cyclic T_xSS tests have been conducted on Saint-Adelphe clay to establish the shear modulus reduction and damping curves of the clay. The Saint-Adelphe clay samples used in these tests had different heights and confinements. Tests N°5 and N°6 have been carried out with samples of 19 mm height and diameter of 62 mm. Tests N°7 and N°8 have been carried out with samples of 25 mm height and diameter of 62 mm. The reinforced membrane has been used for tests N°5 and N°7 and unreinforced rubber membrane has been used for tests N°6 and N°8.

4 METHODOLOGY

The samples used for monotonic tests have been extruded from the Shelby tube and cut to the desired height and diameter. The samples are fitted in the TxSS cell, and the target confinement is applied. The samples are then saturated and consolidated with the same procedures of the standard triaxial test (ASTM-4767). The monotonic tests have been carried out by using strain controlled conditions with shear strain rate ranging between 0.10 % and 0.14 % of the sample height. The tests were performed in a fully undrained condition. The same preparation, saturation, and consolidation procedures of the sample have been adopted in these tests.

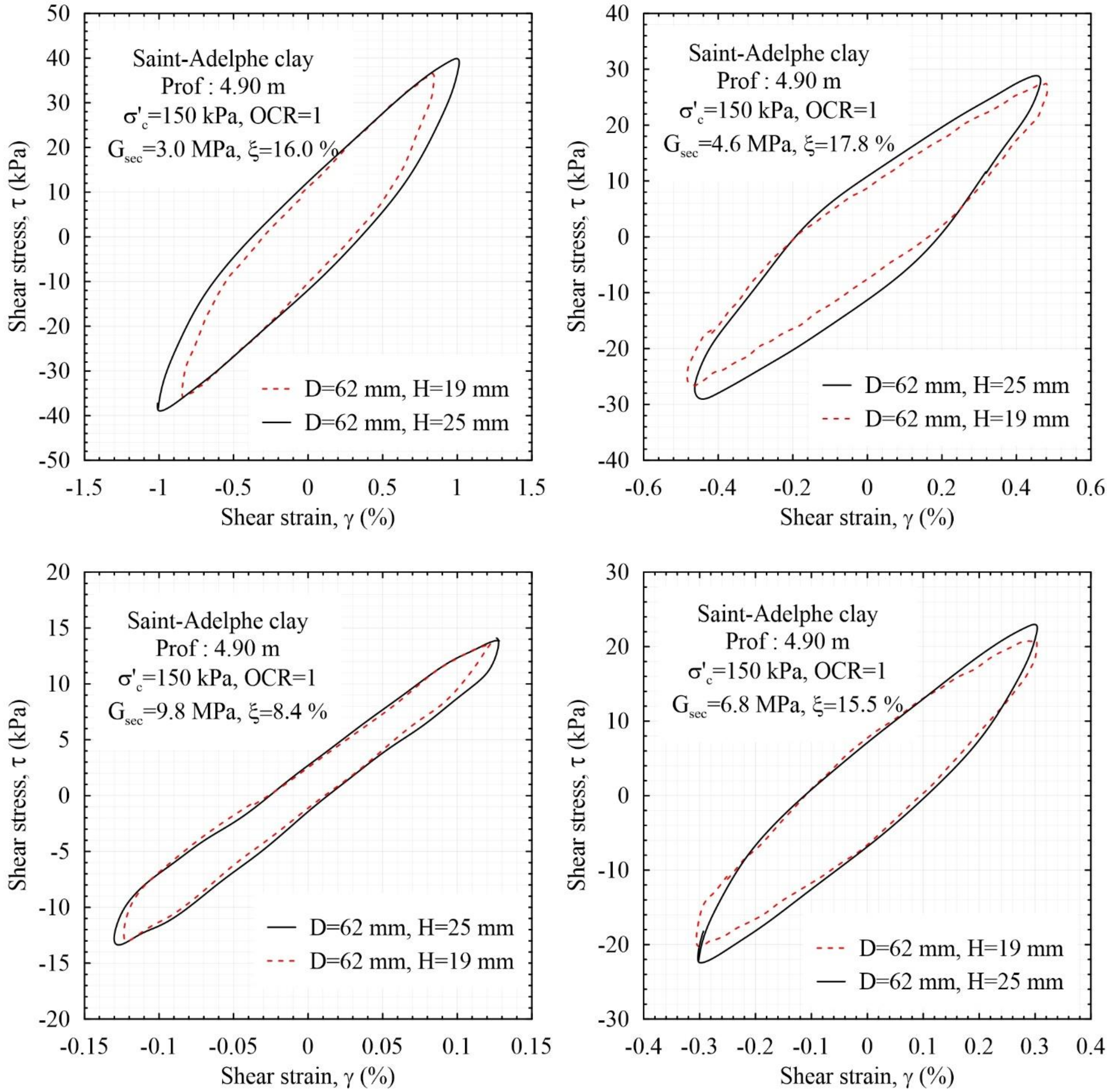

Figure 3 : Influence of the height of the specimen on the results of cyclic tests

The damping ratio and the secant shear modulus of the tested soil are determined from the hysteresis loop obtained by applying a horizontal shear strain. The method followed in this study is the same as the method proposed by Seed and Idriss (1970). The sample are subjected to six cycles of a given shear strain with a sinusoidal signal. The secant shear modulus is obtained from the average secant shear modulus of each loop and the damping ratio is obtained with the following equation:

$$\xi = \frac{A}{2\pi G \gamma^2} \tag{1}$$

where A is the area inside the loop, G is the secant shear modulus and γ is the applied cycle shear strain.

5 EXPERIMENTAL RESULTS

5.1 Monotonic tests results

The results of the five monotonic T_xSS tests are presented in Figs. 1 and 2. The same shape of stress-strain and excess pore pressure-strain curves have been observed for the five T_xSS tests: The strength increases rapidly at small strain and with the increase of shear strain the strength becomes approximately constant.

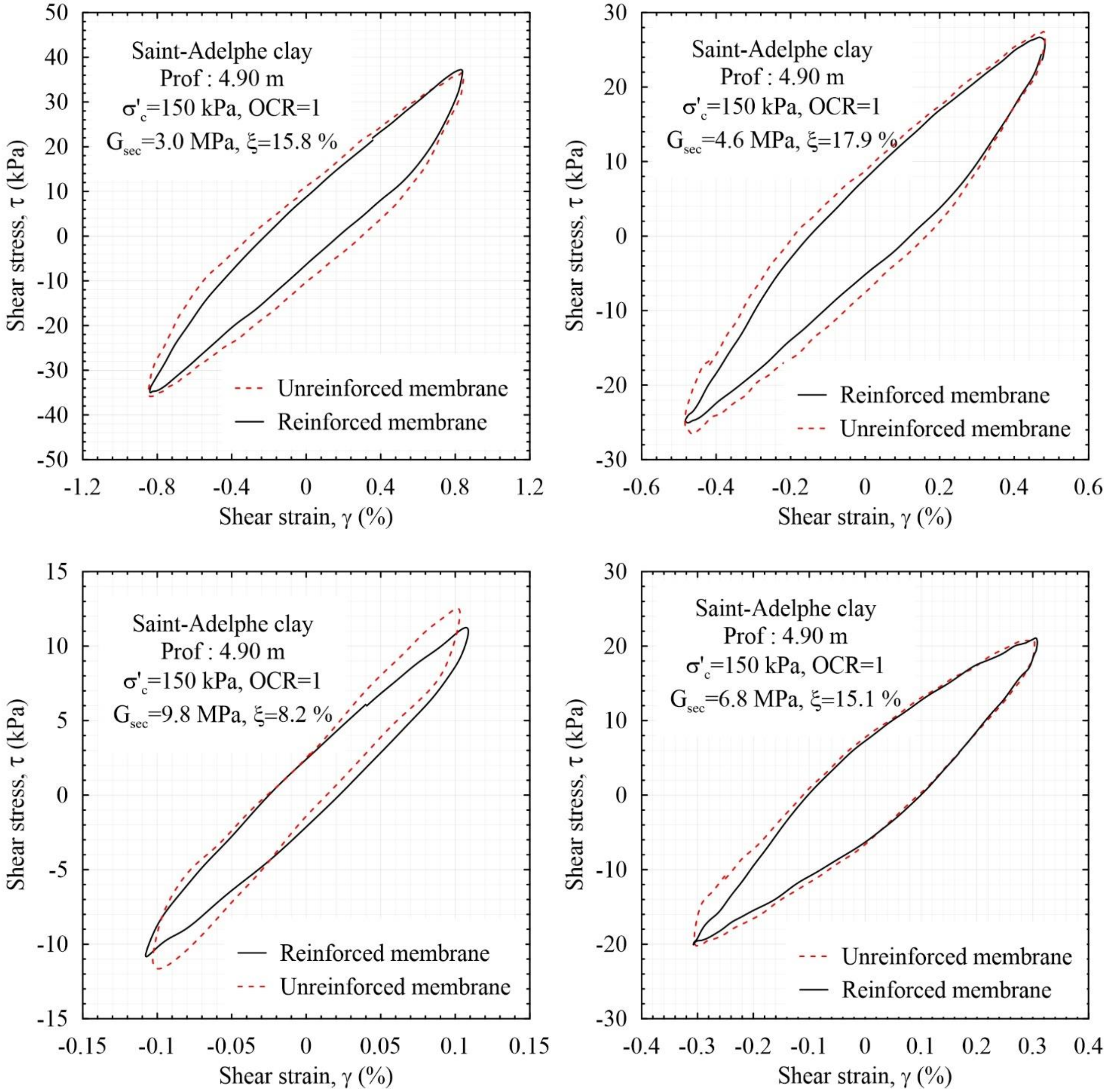

Figure 4 : Influence of the confinement method on the results of cyclic tests.

The results show that there are no clear peaks in the obtained shear stress-shear strain curves of the overconsolidated clay tested in the TxSS apparatus. Instead, a slight strain-softening behaviour was observed in some tests. For excess pore pressure results, it was observed that there is small change in pore pressure with some fluctuation depending on the test. Figure 1-a and 1-b compare the monotonic undrained T_xSS tests with different height with unreinforced membrane. The results show that the tests on sample heights of 19 mm and 25 mm present the same shear strength at small deformation with 21 kPa, and after the peak the two samples present a light strain-softening behaviour with shear strength at large-strain 20 kPa and 17 kPa for the samples of 19 mm and 25 mm respectively. The curves of excess pore pressure show a small generation of pore pressure for the three tests with maximum of 9 kPa. Figure 1-c and 1-d present the monotonic undrained TxSS tests with different height with reinforced membrane. The stress-strain curves show that the test with 19 mm height present 21 kPa of small strain shear strength and 20 kPa large strains shear strength.

The test on sample of 15 mm height doesn't show a peak shear strength at small strain and at large strain the shear strength is approximately the same as the test with sample height of 19 mm with a value of 20 kPa. The curves of excess pore pressure show that the test with 19 mm height generates 8 kPa at small deformation and stays approximately constant at large deformation; however the test with 15 mm height shows a small generation of pore pressure at small strain and decreases at large deformation to 4 kPa. The results presented in Fig. 1 do not show a clear influence of the specimen height on the results of the simple shear monotonic tests.

Figure 2 compare the monotonic undrained T_xSS tests with different confinement methods. Figure 2-a and 2-b compare the tests of the sample of 15 mm height. The stress-strain curves show that the two tests give the same results with a hyperbolic curve. The curve became approximately constant at large deformation with shear strength about 21 kPa. The curves of pore pressure show the same behaviour at small deformation, however at large deformation some difference appears with 6 kPa for the test with reinforced membrane and – 4 kPa for the test with unreinforced membrane. Figure 2-c and 2-d compare the tests of the samples of 19 mm height. The curves of shear strength show some difference at small-strain with value of 18 kPa and 22 kPa for the tests with reinforced and unreinforced membrane respectively. At large deformation, the two samples give the same shear strength with value of 20 kPa. The result of figure 2 shows that the use of reinforced or unreinforced membrane does not considerably affect the results of TxSS tests.

5.2 Cyclic tests results

The results of cyclic undrained T_xSS tests on Saint-Adelphe clay specimens with different height and confinement methods are presented in Figs. 3 and 4. The specimens used for these tests are from 4.90 m depth. The tests have been carried out on specimens saturated and consolidated to effective stress equal to 150 kPa where the specimens are on normally-consolidated domain. In Fig. 3, different loops of shear stress-shear strain of the first cycle for a given maximum applied shear strain of two different height specimens (19 mm and 25 mm) are presented. These tests have been carried out on specimens confined with unreinforced membrane. The results show no significant difference in the secant shear modulus and damping ratio for the four tests of maximum shear strain 0.1 %, 0.3 %, 0.5 % and 0.8 %. These results indicate that results of cyclic TxSS tests are not affected by the change of the height of the specimen from 19 mm to 25 mm. These results are consistent with earlier findings of Carrol (1979). In Fig. 4, the results of four cyclic undrained TxSS tests on specimens with different confinement methods are presented. The specimens are saturated and consolidated to 150 kPa of effective vertical stress σ'_{vc} for the specimen confined with reinforced membrane and effective confinement stress σ'_c for the specimen with unreinforced membrane. The results show that the four tests with maximum applied shear strain 0.1 %, 0.3 %, 0.5 %, 0.8 % show no significant difference in secant shear modulus as well as the damping ratio. These results indicate that the cyclic tests with specimen confined with reinforced membrane or unreinforced membrane give approximately the same results.

6 SUMMARY AND CONCLUSIONS

The effects of specimen size and confinement method on the results of monotonic and cyclic undrained simple shear T_xSS test conducted on two sensitive clays have been studied in this paper. Two series of undrained T_xSS tests on sample with different heights and confinement methods have been carried out in the T_xSS apparatus. The following observations have been made:

- The results of simple shear TxSS tests with two confinement methods give approximately the same results in monotonic and cyclic loadings.
- The tests with different height do not show a clear influence of the change of the height of the sample on the stress-strain curves of the monotonic tests as well as the cyclic tests, however some fluctuation was observed in the pore pressure generation.

It should be noted that these tests have been carried out on quick clays and the generalization of these observations to other type of clays is not evident since the variability of the soil could affect considerably the results. Therefore, more research is needed to confirm these observations on other type of clays.

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