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Shear Strength of a Sand Under Plane Strain Conditions

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Abstract. Laboratory tests are performed to simulate, in the best way, the observed field conditions. These conditions assist in the choice of the test to be performed for the determination of the relevant geotechnical parameters. Among the tests used in Geotechnical Engineering, simple shear stands out. This test is known and used to measure shear strength and soil stiffness. Further, it is the only laboratory test capable of imposing on a sample plane strain conditions under constant volume and allowing rotation of principal stresses. A few of the most common applications of the simple shear testing are the vertical shear wave propagation through a soil column, the mode of shearing to a pile shaft and under an offshore gravity base platform. In this context, simple shear apparatus was developed with the purpose of analyzing the behavior of materials under such loading conditions. The study was conducted in a fine uniform sand from the city of Osorio, Brazil. The Osorio sand showed a behavior typical of medium dense sands with stress envelope with the angle of 35º. Results presented a peak of shear stress followed by reduction of resistance. Furthermore, the three initial effective stress carried on this research showed a normalized behavior during shear strain. The cyclic tests presented the same stress envelope as the monotonic test, reaching also the angle of 35º. As expected, a stiffness degradation for a wide range of shear strain was observed.

Keywords. Simple shear tests, monotonic loading, shear stress of soils.

1. Introduction

Laboratory tests are performed to simulate the observed field conditions. Simple shear tests are often preferred when the continuous rotation of the principal stress directions during shearing is observed. A few of the most common applications of the simple shear testing are the vertical shear wave propagation through a soil column, the mode of shearing to a pile shaft [1] and under an offshore gravity base platform [2].

Most simple shear apparatuses, in order to impose no lateral distortion, enclose the soil in a rubber-reinforced membrane [3] and [4]. A near K_0 condition is assumed to be obtained in this type of equipment. Differently, recent devices, such as the University of Western Australia (UWA) equipment, enclose specimen in an unreinforced latex membrane inside a pressurized cell [5]. The vertical and cell pressures are controlled independently. With the equipment software routine, total vertical stress and sample height are kept constant during shearing. In order to achieve such conditions, the vertical loading ram is locked and the cell pressure varies to keep total vertical stress constant.

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Once height and volume are constant (undrained tests), average cross-sectional area is likely to remain constant.

This paper describes the design of a simple shear apparatus, based on the UWA apparatus. The equipment was designed, manufactured and calibrated at the Federal University of Rio Grande do Sul. Tests were carried out using a well-known uniform sand to validate the equipment.

2. Simple Shear Tests

2.1. Previous work

Simple shear tests have been used for many engineering and geology purposes, such as the study of mechanical behavior of sands [5], clays [6] and mine tailings [7], and the modeling of folding and fracture patterns. The equipment development started with an apparatus by Ansell & Brown [3] to overcome some of the shortcoming of the traditional direct shear test, which suffers from non-uniform stress distributions throughout the specimen. Typically, the test consists of a circular specimen, consolidated to a stress level under K_0 conditions.

The aim of all apparatuses was to apply a simple shear mode of deformation to a soil specimen, but the need for the ends of the specimen to extend during shearing means that complementary shear stresses are not generated on the ends [8]. Because of this, the shear stress is non-uniform across the top and bottom of the specimen, falling to zero at the corners. The resulting unbalancing couple has to be counteracted by an opposite couple generated by a non-uniform distribution of normal stress on the top and bottom of the specimen surface [9].

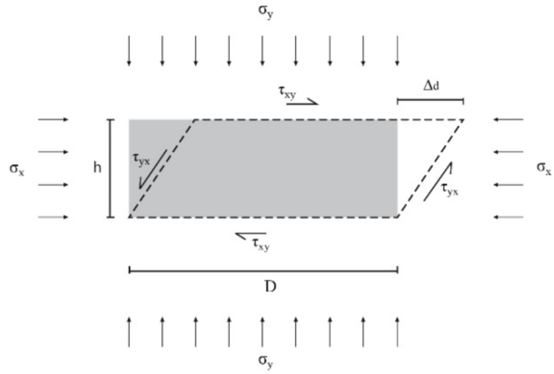
Festugato [10] investigated two different aspects of the simple shear devices. The different total stress paths followed by devices that impose constant cross-sectional area using a stiff external boundary, and those that use a constant total stress lateral boundary condition were explored. This was done by conducting finite element analysis of a single cubic element. The authors observed that this element might be subjected to perfect simple shear using four different boundary condition types. Each boundary condition type results in the same effective stress path, but different total stress paths and excess pore pressures. However, significant differences in total stress path and excess pore pressures occur among the four boundary condition types.

2.2. Description of the apparatus

The simple shear device of the Federal University of Rio Grande do Sul (UFRGS) was designed to confine samples with a membrane through confining pressure. In the developed apparatus, samples height is kept constant during shearing and total vertical stress is constant. The maximum horizontal displacement a sample can achieve during shearing is 25 mm.

Figure 1 presents the basic definitions of the simple shear apparatus. In Figure 1, σ_y is the vertical stress, σ_x is the horizontal stress, D is the diameter of the specimen, h represents the height of the specimen, τ_{xy} is the shear stress, ε_x is the horizontal strain, ε_y is the vertical strain and γ_{xy} is the shear strain.

Shear stress τ refers to the shearing loads on the horizontal direction, while the strain caused by shearing, γ, is the ratio between the horizontal displacement and height of the specimen.



$\tau_{xy} = \sigma_x \quad \gamma_{xy} = \frac{\Delta d}{h} \quad \varepsilon_y = \frac{\Delta h}{h} = 0 \quad \varepsilon_x = 0$

Figure 1. Basic definitions of the simple shear apparatus.

The principal requirement of the apparatus design was that all test phases could be controlled and monitored by software. Also, the instrumentation should be as close as possible to the soil sample.

3. Experimental Program

3.1. Materials

Osorio sand was chosen due to its widely known behavior and extensively investigation in the past 20 years at the Federal University of Rio Grande do Sul (UFRGS, Brazil) using distinct laboratory testing, such as plate load tests [11], ring shear tests [11], direct shear tests [12], isotropic compression tests [13] and triaxial compression tests [14] and [15].

The sand is classified as uniform fine sand. Quartz corresponds to 99% of the mineralogical composition. Osorio sand has a specific gravity of solids of 2.62; uniformity coefficient, C_u, of 2.1; curvature coefficient, C_c, 1.0; its effective diameter, D_{10}, is 0.09 mm; mean diameter, D_{50}, 0.16 mm, minimum void ratio, e_{min}, 0.6 and maximum void ratio, e_{max}, 0.9.

Specimens were prepared with a split mold. The sand was manually mixed with 10% of water and compacted in two layers by tamping inside the mold at a relative density of 50%. The size of the specimens was fixed with diameter of 100 mm and 50 mm high. The latex membrane was positioned inside the mold, which has a hollow to apply vacuum. A vacuum pump was used to approximate the latex membrane to the mold during sample compaction. O-rings were used for sealing. Once the specimen was prepared, top cap was positioned and the set was put in the apparatus. Figure 2 presents the method of preparation of specimens and the test procedure: (a) insertion of saturated porous stone on top and bottom cap; (b) placing of saturated filter paper; (c) preparation of latex membrane inside split mold; (d) vacuum application; (e) compaction of soil specimen;

(f) finalization of specimen preparation and cleaning of the membrane surface; (g) insertion of the top cap; (h) insertion of specimen on the simple shear apparatus; (i) specimen after shearing

Figure 2. Specimen preparation and test procedure.

3.2. Test Procedure

The main focus of the tests was to validate the equipment. Thus, tests were carried out with monotonic and cyclic loading. Specimens were tested with relative density of 50%. The initial effective stresses were 50, 100 and 150 kPa for the monotonic loading and 100 kPa for the cyclic loading. For all tests the backpressure was 300 kPa and the confining pressure was changed according to the initial effective stress. This range of effective stresses was chosen so that the results observed in this research could be compared against previous works that studied similar levels of effective stresses [11], [14] and [12].

Shearing was performed under undrained conditions. For monotonic tests, the displacement rate of 0.1 mm/s was adopted based on previous work of [16]. Monotonic simple shear tests were analyzed through shear stress-shear strain, pore pressure variation-shear strain, variation of vertical effective stress-shear strain curves and stress paths. From the curves, strength and stiffness parameters are defined: effective internal friction angle, γ’, and shear modulus, G, respectively.

4. Results

Figure 4 presents results of the monotonic test at the initial effective vertical stress of 50, 100 and 150 kPa. The sandy matrix under undrained simple shear conditions presents slightly pronounced strength peak, followed by a shear stress reduction associated with the increase of pore pressure (Figure 3).

The shear stress rises up to a level around 50 kPa falling to about 40 kPa until 10% strain for the specimen tested with an initial vertical effective stress of 50 kPa. After this fall, the sand specimen regains strength.

The specimen tested with 100 kPa of initial vertical effective stress exhibited similar behavior to the 50 kPa test. Under undrained monotonic simple shear conditions the sandy soil presented a slightly pronounced strength peak. The shear stress increased up to a level of 85 kPa falling to about 80 kPa at 22% strain. Analogous behavior was observed for 150 kPa initial effective vertical stress.

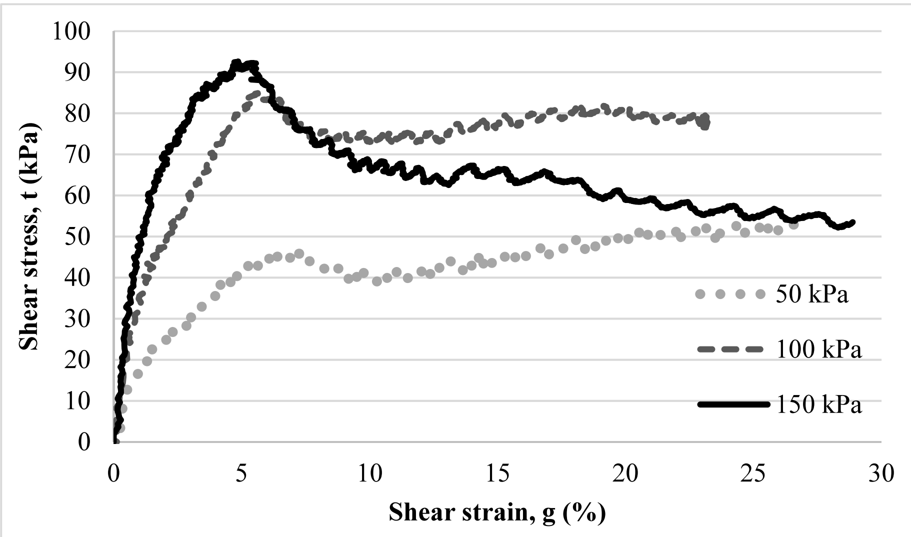


Figure 3. Shear stress versus shear strain (σ'_v = 50, 100 and 150kPa).

The variation of pore pressure and effective vertical stress is presented on Figure 4. For the test conducted with initial effective vertical stress of 50 kPa, the variation of pore pressure increases to around 7 kPa at 3% strain. After that, the pore pressure increment decreases until the end of the test when it comes to -90 kPa. In response to pore pressure variation, to guarantee plane strain conditions with constant volume, effective vertical stress initially at 50 kPa is reduced to 43 kPa at 3% strain. It then undergoes a gradual increase, reaching 140 kPa at a strain of 33%.

On test of 100 kPa of initial effective vertical stress, the pore pressure increment increased up to 15 kPa, reducing afterwards to -90 kPa upon reaching the deformation 20% and continued to reduce until the end of the test. In response to increasing pore pressure, to guarantee conditions of plane strain with constant volume, the effective vertical stress initially at 100 kPa reduced to 85 kPa, reaching afterwards 190 kPa at 20% strain.

With an initial effective stress of 150 kPa, pore pressure increases to a value of 36 kPa and remains constant until the end of the test. Effective vertical stress reduces to 114 kPa in response.

In Figure 5 the results are presented in the p' versus q. Results show the same behaviors to all tests until it reaches the maximum value of q in each the test.

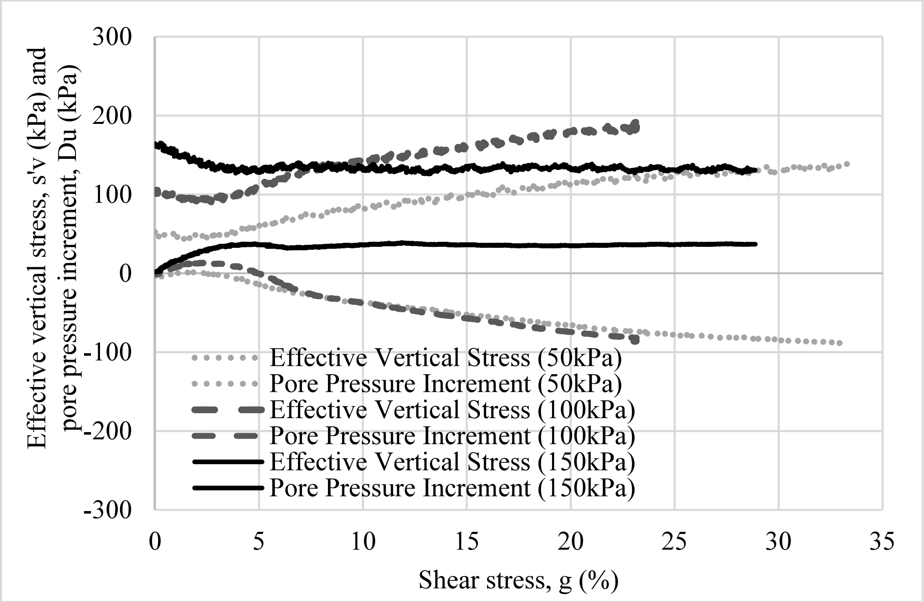


Figure 4. Effective vertical stress and pore pressure increment versus shear strain (σ'_v= 50, 100 and 150 kPa).

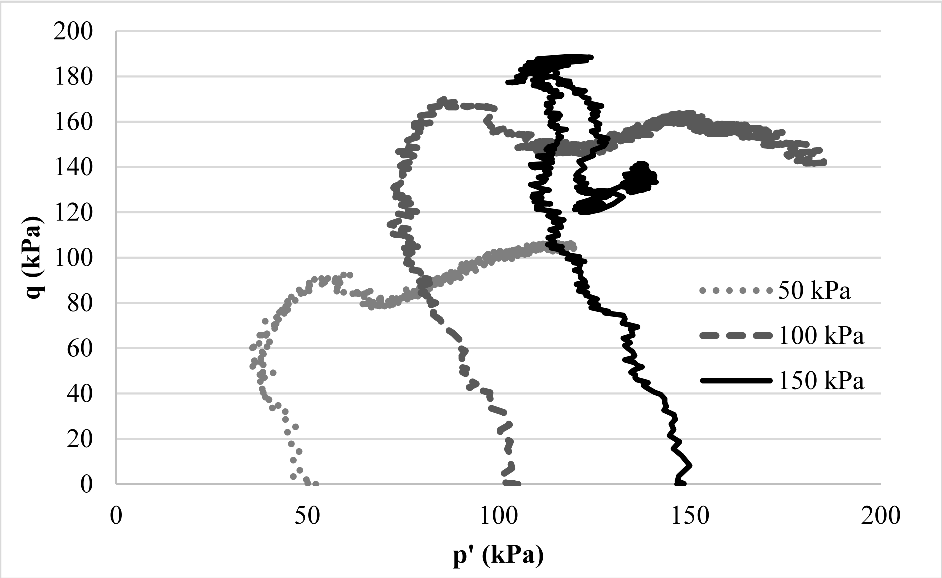


Figure 5. p' versus q (σ'_v = 50, 100 and 150 kPa).

The shear modulus (G) variation with shear strain is presented in Figure 6. It can be observed that the three analyzed stresses had very similar shear modulus variation trend. As shear strain evolves the shear modulus degrades. [17] and [18] observed also a stiffness degradation for a wide range of shear strain.

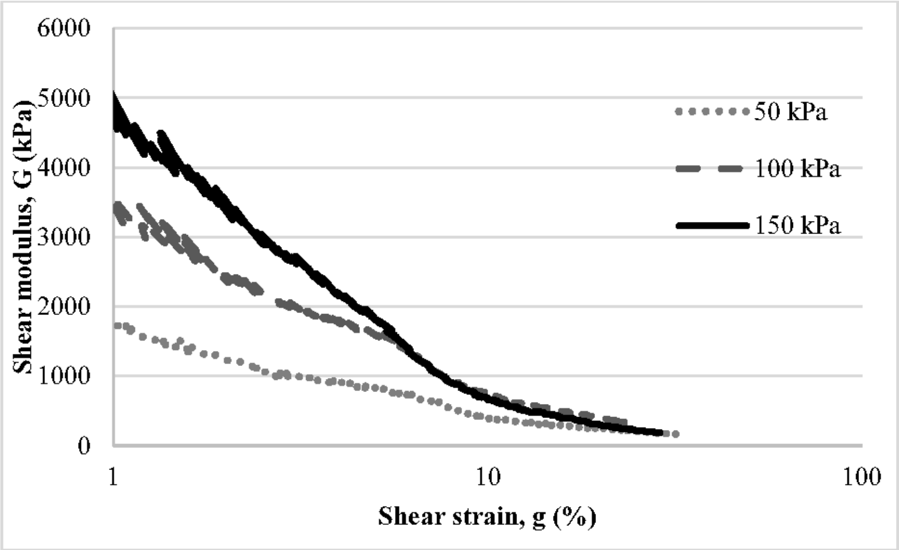


Figure 6. Variation of modulus (G) with shear stress.

Figure 7 shows the results of the tests in the plane σ'_v x τ. It can be noticed that all paths present a peak of resistance followed by the decrease of shear stress. The internal effective friction angle observed to this sand was 35°.

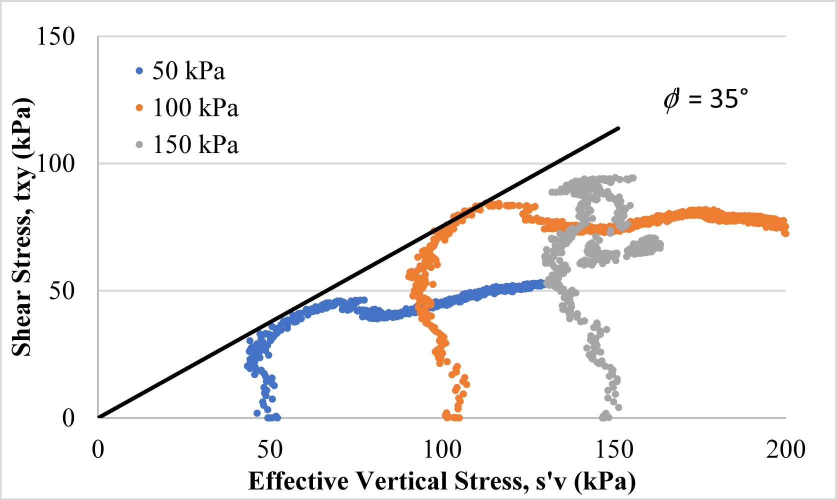


Figure 7. Strength envelope for the tests.

In order to validate the developed apparatus, the strength parameters derived from the testing of this study were compared against literature results (Table 1). It was found compatibility of the results obtained for the Osório sand with previous studies on this same material. Four distinct researches were evaluated. Three of these performed triaxial tests [11], [14], [12] and one of them carried out direct shear tests [12].

Table 1. Test analyzed to compare the strength parameters

Autor	Test	D_r (%)	e (%)	σ'_v (kPa)	ϕ' (°)
[11]	Triaxial	50	0.75	20. 100. 200 and 400	33.5
[14]	Triaxial	50	0.75	50, 100 and 200	37
[12]	Triaxial	67	0.71	50, 100 and 200	35.9
[12]	Direct Shear	67	0.71	50, 100 and 200	34.9
This research	Simple Shear	50	0.75	50, 100 and 150	35

5. Conclusion

A simple shear apparatus has been developed to test soil samples. The apparatus uses internal monitoring instruments. The results of the simple shear tests presented in this paper indicate that the equipment has consistent and adequate quality results. When results of the simple shear tests are compared against results on this same Osorio sand from literature, values are comparable. Unlike usual triaxial tests, the simple shear test presents the advantage of allowing the simulation of complete rotation of the stress state by imposing a plane strain condition.

Despite the limited number of performed tests, the observed results were consistent and presented good agreement. A sound indication of that is the same strength envelope limiting all stress paths. The results presented in Table 1, show very low variety from the internal friction angle obtained on the simple shear. From literature, minimum value found was 33.5° an maximum was 37°, the average was 35.3. Simple shear tests performed obtained a strength parameter ϕ' 35°. The shear strength parameter obtained in triaxial tests showed minimum variations compared with the value found with the simple shear apparatus. When compared to the direct shear test, the internal friction angle obtained through the simple shear tests varied very little.

Due to the reasons cited above, the equipment developed was considered satisfactory for the execution of simple shear tests. New researches will be developed using this same equipment.

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