Earth Reinforcement, Ochiai, Yasufuku & Omine (eds) © 1996 Balkema, Rotterdam. ISBN 90 5410 833 9

Experimental analysis of friction between sand and reinforcing elements using ring simple shear tests

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ABSTRACT: Behavior of interfaces between soils and reinforcing elements plays a key role in the design and analysis of civil engineering structures, such as reinforced backfills or soil nailed structures. In this paper, we present a new laboratory device, the ring simple shear apparatus, especially designed for studying and measuring friction between sand and reinforcing elements. The principle of the apparatus is to revolve a rigid steel cylinder (modeling the reinforcement) in an annular sample of soil. The results presented herein are obtained with samples of Hostun sand (D_{50}=0.36 mm) or Hostun gravel (D_{50}=3 mm). The cylinder used have smooth or rough surfaces. The results show that the main factors which affect the friction and its mobilization are the nature of the surface, the nature and the density of the soil and the overburden pressure. Results of cyclic test show the degradation of the mobilized friction with the number of cycles.

1 INTRODUCTION

Behavior of interfaces between soils and reinforcing elements plays a key role in the design and analysis of Civil Engineering structures, such as the reinforced backfills or soil nailed structures. These technologies are based on the development of friction between the soil and the reinforcements.

Early works on the skin friction properties between a solid body and granular material were performed using a modified direct shear box (Potyondy, 1961; Butterfield and Andrawes, 1972). Some improvements and modifications have been made to that direct shear box to reduce its defects (Wernick, 1977).

Several sophisticated devices have also been developed: an annular shear device (Brumund and Leonards, 1973), a ring torsion apparatus (Yoshimi and Kishida, 1981; Boulon, 1988) and a simple-shear-type apparatus (Uesugi and Kishida, 1986).

But all these devices present shortcomings : the boundaries imposed on the sample have a strong influence on the results. Stresses concentrate at the ends of the interface (modified direct shear box and annular shear device) or the displacement across the interface (i.e. shear strain in the sample) isn't constant (ring torsion apparatus).

This present paper describes a new laboratory device, named ring simple shear apparatus. The test results are analyzed to put into evidence the main factors which affect the friction and its mobilization: nature of the reinforcement, nature and density of the soil and external radial pressure.

2 THE RING SIMPLE SHEAR APPARATUS

2.1 Principle of the ring simple shear test

The ring simple shear apparatus simulates the shearing of a thick wall cylinder of granular material in plane strains by a cylindrical inclusion submitted to torsion (figure 1).

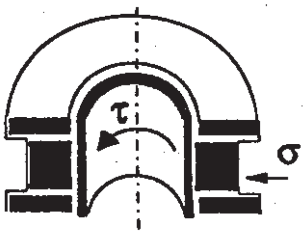


Fig.1 Principle of the ring simple shear test

2.2 Apparatus and test procedure

Figure 2 presents a picture and a global view of the ring simple shear apparatus. The height of the apparatus is 1500 mm for a weight of 6000 N. The annular sample of granular material, around the rigid cylinder, has the following dimensions: 100 mm in height, 100 mm of inner radius, 200 mm of external radius. An outer membrane applies the external confinement to the sample, by water controlled by a pressure - volume controller. The plane strains are obtain by two steel plates of 80 mm thickness. Three hydraulic jacks on the top of the sample apply a uniform vertical stress which can be chosen during consolidation to generate an initial isotropic state or a "Ko" one.

The rigid cylinder applies a shear stress at the interface though a couple transmitted by an electric motor with reduction of 8000 Nm. An optoelectronic incremental encoder measures the rotation and a bridge of gauges reads the torque. In addition, normal stresses are measured directly at the interface with specifically designed cells. Both microscopic grain displacements and macroscopic deformations are observed through a glass window located at the bottom plate. The ring simple shear apparatus is controlled automatically by computer.

Tests using different types of soil (sand, gravel), roughness of interface, consolidation and boundary conditions (constant normal stress, constant volume, constant stiffness) can be performed to understand the influence of the soil and therefore parameters on the properties and behaviour of the interface layer. The rate of shearing can be constant (monotonous tests) or alternate (cyclic tests). The initial radial stresses applied are between 100 and 600 kPa. The confining pressure can be compared to the overburden pressure which exists around a reinforcing element. Test are performed without loss of material and structure, can be continued up to very large displacements.

The apparatus, in its most simple configuration, allows the use of Schneebeli model rolls for studying the deformations of the sample and the rotations of the grains within the interface layer. This test is perform at a constant normal stress which is applied by a hydraulic annular membrane.

3 TEST PROGRAM AND RESULTS

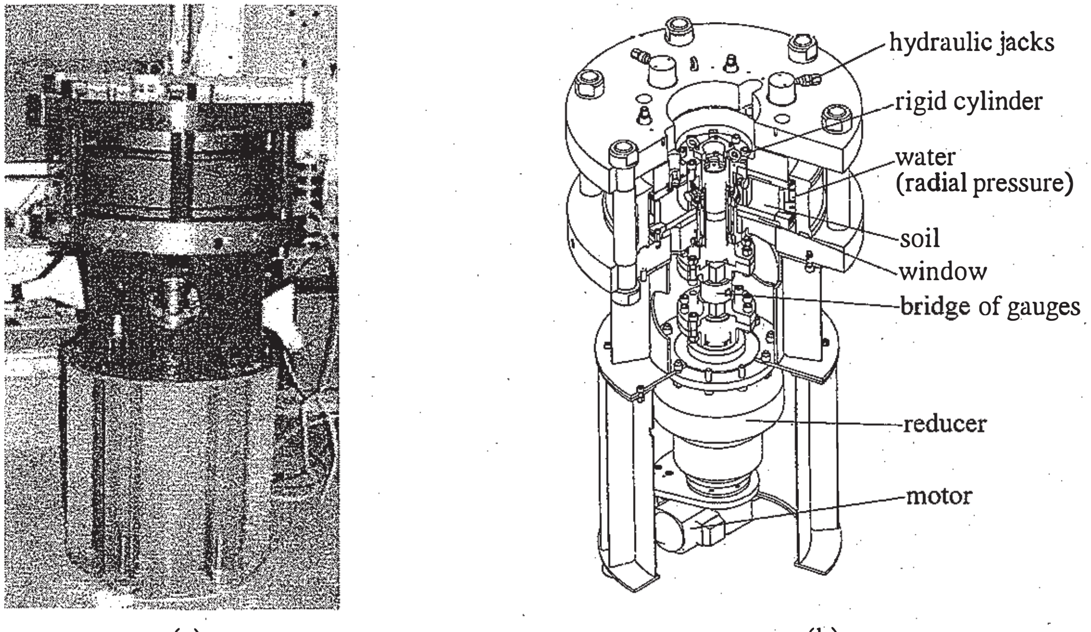
3.1 *Material properties and interface roughness*

The tests are performed with two types of granular materials: Hostun RF sand and Hostun 14~10 gravel. Table 1 provides properties: mean grain size (D_{50}), minimum and maximum void ratio (e_{min} and e_{max}), specific gravity (ρ_s), minimum and maximum densities ($\rho_{d\ min}$ et $\rho_{d\ max}$), coefficient of uniformity (Cu) and gradation (Cc).

Two different roughnesses are used. The smooth interface has a value of R_{max} of 15µm (as defined by Yoshimi and Kishida, 1981) and the rough surface has been obtained by milling of grooves ($R_{max} = 2$ mm).

3.2 *Test program and results*

Altogether forty tests were carried out under different conditions. We present here four series of tests. Two are performed between dense sand and

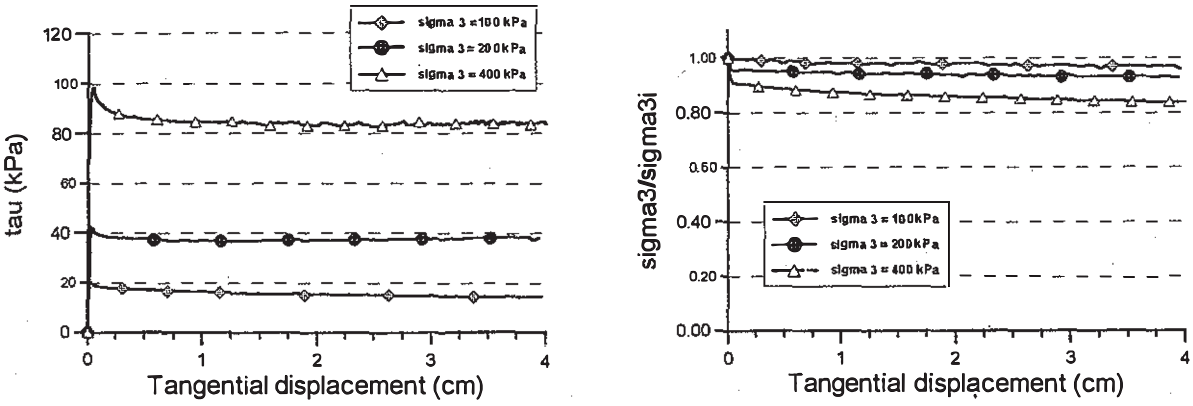


(a) (b)

Fig. 2 (a) Picture and (b) global view of the ring simple shear apparatus

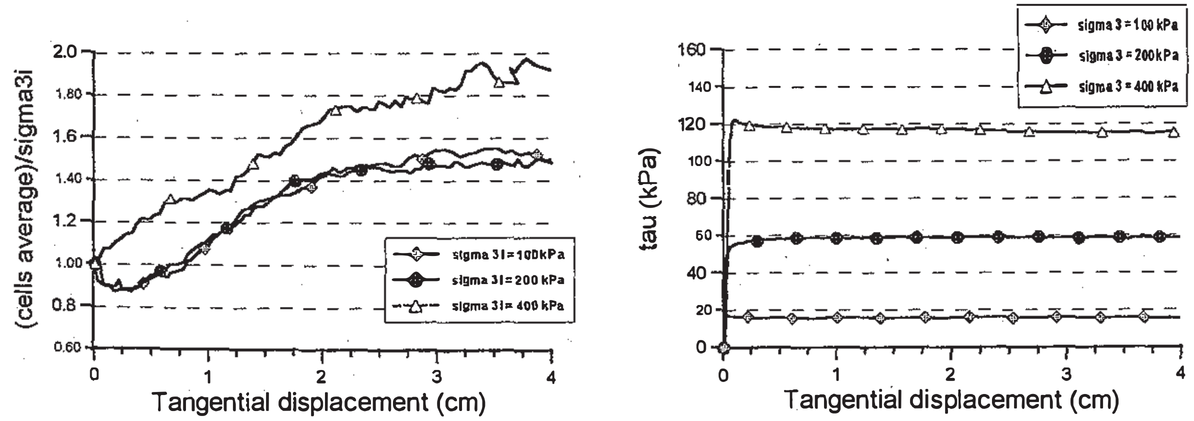
Table 1 Material properties of the granular materials used in testing

Material	D_{50} (mm)	e_{min}	e_{max}	ρ_s (t/m^3)	ρ_{dmin} (t/m^3)	ρ_{dmax} (t/m^3)	Cu	Cc
RF sand	0.32	0.624	0.961	2.65	1.32	1.60	1.60	0.85
14~10 gravel	3.30	0.45	0.81	2.65	1.46	1.83	1.40	1.10



(a) Shear stress versus tangential displacement

(b) External radial pressure

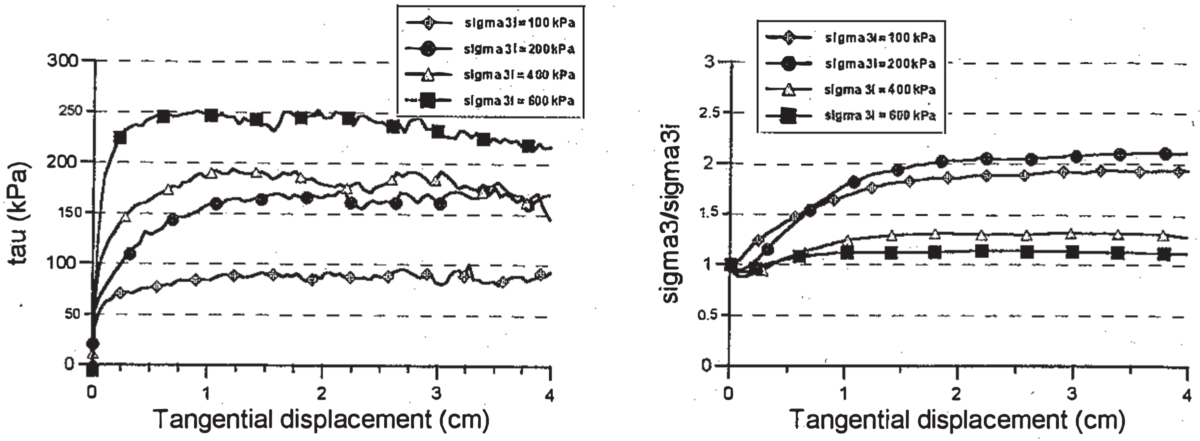


(c) Local normal stress

(d) Shear stress

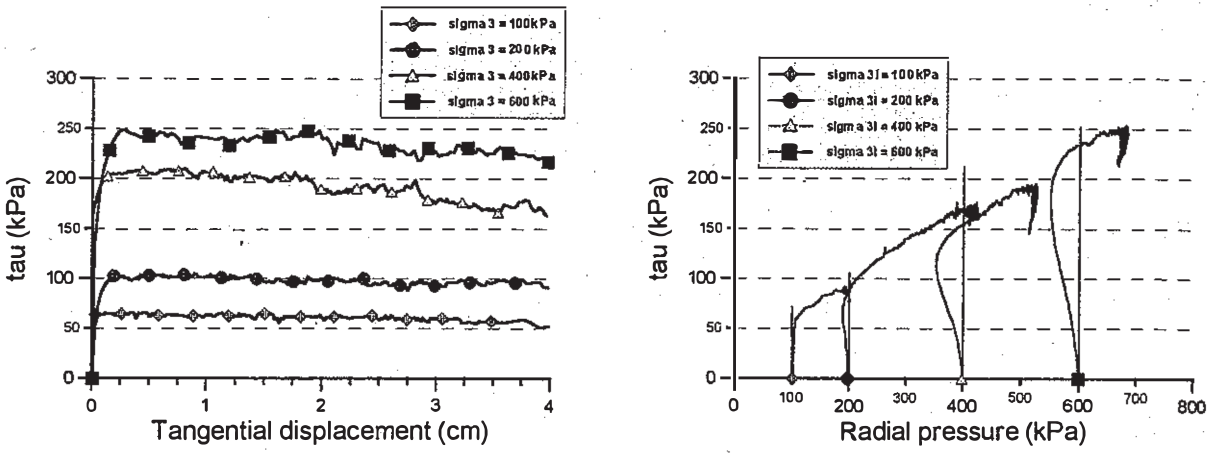
Fig. 3 Ring simple shear test results for Hostun RF dense sand at constant volume (a, b and c) and at constant normal pressure (d) with a smooth interface

smooth interface, one at constant volume and one at constant radial pressure, with local measurement of the normal stress at the interface, at three different initial external radial pressures (figure 3). Two other series were performed between dense gravel and rough interface, one at constant volume and one at constant radial pressure, at four different initial confining pressures (figure 4). These tests allow the analysis of the influences of boundary conditions and type of soil. The comparison between the tests with sample of loose gravel and sample of dense gravel shows the influence of the density (figure 5) and the comparison of tests with rough and smooth interfaces shows the influence of the roughness (figure 6). All these tests are performed with a constant rate of shearing (1 mm / min) and with a K_0 consolidation. The presentation of a cyclic test shows the degradation of the shear stress with the number of cycles and the variation of the initial confining pressure (figure 7).



(a) Shear stress

(b) External radial pressure



(c) Shear stress

(d) Shear paths in (τ, σ) plan

Fig. 4 Ring simple shear tests results for Hostun 14~10 dense gravel at constant volume (a, b and d) and at constant radial pressure (c and d) with rough interface

4 TEST RESULT INTERPRETATION

The results with sand samples shows the predominance of the local behavior, inside the interface zone, during the shearing. The maximum values of the shear stresses are obtained for small displacements of the order of 1 mm, i.e. 2 to 4 times the average grain diameter. During tests at constant volume, the variations of the external radial pressure shows a global contractancy of the sample (figure 3b) even though stress measurements at the interface by local cells tend to show a small phase of contractancy followed by a strong phase of dilatancy within interface layer (figure 3c).

For the tests performed with gravel samples, the shear stress reaches its maximum value for tangential displacements of 8 to 12 mm for constant volume tests (figure 4a) and 2 to 3 mm for constant radial pressure (figure 4c) to be compared to the grain diameter ($D_{50} = 3.30$ mm). The initial phase of global contractancy of the sample is followed by dilatancy as indicated by the external radial pressure variation (figure 4b). The contractancy is characterized by a decrease in the external pressure and the restrained dilatancy (Schlosser and Guilloux, 1981) by a increase in the external pressure.

Figure 4d shows the stress paths for the eight tests on the gravel. They determine a line of failure corresponding to friction angle of 23° which varies slightly in average with the real radial pressure.

4.1 Influence of the initial external radial pressure

The real friction coefficients ($\mu = \tau_{max}/\sigma_3$) and the apparent friction coefficients ($\mu^* = \tau_{max}/\sigma_{3i}$) are higher for the strong initial external pressures in the case of sand sample with a smooth interface and lower for the strong initial external pressure in the case of a gravel sample in a rough interface. These features are directly connected to the behavior observed with the measurement of the variations of the external radial pressure: in the first case, the sand sample contracts more and the dilatancy in the interface is bigger with the strong pressure and, in the second case, the gravel sample dilates more with the low pressure. Some complementary tests with low external pressure are necessary to complete this analysis.

The observations though the windows at the bottom of the sample always shows that crushing of gravel grains is more important at higher external radial pressure, explaining the less relative dilatancy.

4.2 Influence of the granulometry

Influence of the granulometry has to be compared to the inclusion roughness and the mean grain size. As obtained by Uesugi and Kishida (1986), the limit surface roughness (R_{max}) between smooth and rough is near $D_{50}/10$. The real friction coefficient for sand is higher than the real friction coefficient for gravel, obtained with the same conditions of testing, on account of the dimensions of the sample. For gravel, the behavior inside the interface (contractancy or dilatancy) has an effect on the response at the external boundary and can thus measured. However, for sand, the thickness of the interface layer is to small as compared to the thickness of the sample and thus, the local dilatancy or contractancy at the interface can't be measured on the external boundary.

4.3 Influence of the density

Figure 5 presents test results with dense sample (relative density $D_r = 0.70$; $D_r = (e_{max} - e)/(e_{max} - e_{min})$) and loose sample ($D_r = 0.33$) of gravel. For loose sample, the maximum shear stress is obtained for a displacement of 0.3 mm and an apparent friction coefficient of 0.22. The pick is followed by a constant decrease. On the other hand, for dense gravel, the maximum value of the shear stress is obtained for a displacement of 10 mm and stays constant on a plateau corresponding to an apparent friction coefficient of 0.82. The ratios for the two friction coefficients are between 4 and 6. This strong difference may be due to the cylinder geometry of the experiment which could generate arching effects.

4.4 Influence of the roughness

Figure 6 presents test results with smooth and rough interface on dense samples of gravel. For a smooth interface, the shear stress reach a pick for a displacement of 1 mm, corresponding to an apparent friction coefficient of 0.18, followed by a plateau. For a rough interface, the maximum value of the shear stress is obtained for a displacement of 10 mm and stay constant for a value corresponding to an apparent friction coefficient of 0.82. The ratios on the two friction coefficients are between 2 for small displacements and 8 for large displacements.

4.5 Influence of the solicitation

Figure 7 presents the result of a cyclic shear test performed on dense gravel, with a rough interface, at constant volume and an initial external radial pressure of 200 kPa. The alternate shearing is obtained by an alternate displacement of the central cylinder of 20 mm. The tangential displacement

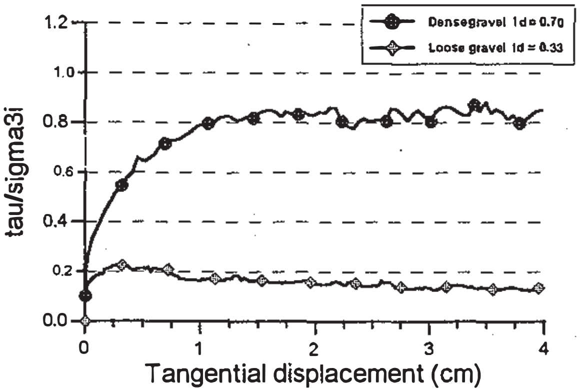


Fig. 5 Influence of the density: results for Hostun 14~10 dense and loose gravel at constant volume with a rough interface

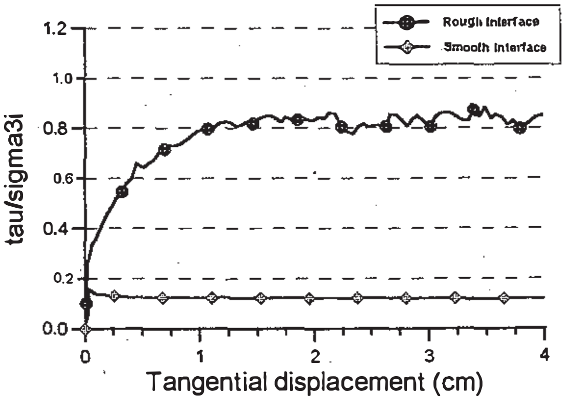
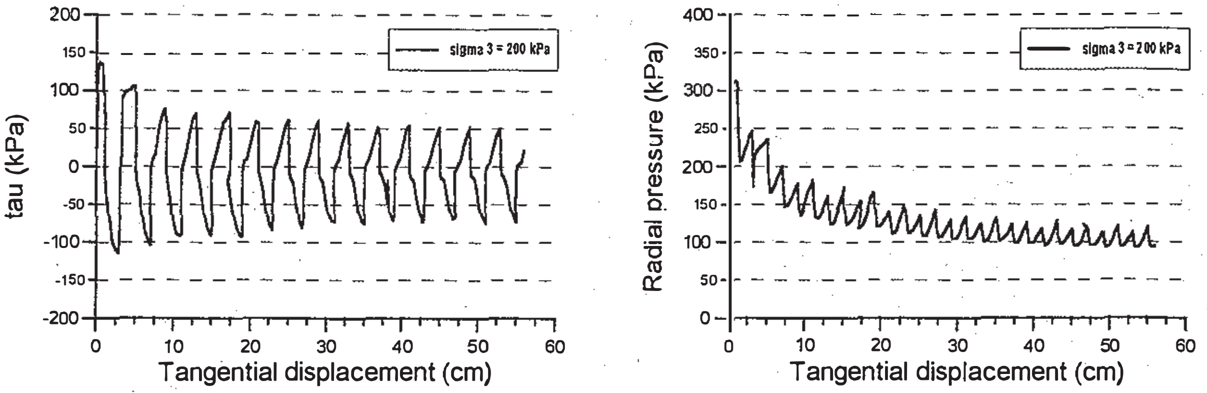


Fig. 6 Influence of the roughness: results for Hostun 14~10 dense at constant volume with smooth and rough interface



(a) Shear stress versus total displacement

(b) External pressure versus total displacement

Fig. 7 Cyclic ring simple shear test results for Hostun 14~10 dense gravel at constant volume (rough interface)

presented on these figures is the total displacement of the interface.

Like a monotonous test, the shear stress reaches a maximum value (140 kPa) before it decreases at the first change of direction of shearing. The maximum value of the shear stress decrease for each cycle before stabilizing at the fifth cycle at 50 kPa. The external radial pressure, after a pick at 315 kPa, decrease to 200 kPa at the end of the first cycle before a re-increase. At each change of direction of shearing, the variation of the external radial pressure also changes direction, with a global decrease reaching 100 kPa, characterizing the global contractancy of the sample.

5 CONCLUSIONS

By its principle, the ring simple shear apparatus enables the assessment of friction mobilization between granular materials and reinforcing elements.

The results presented allows us to measure the influence on the mobilization of friction of: nature of the surface, nature and density of the granular material and initial external radial pressure. The observation of the interfacial layer shows the influence of the crushing of grains in the development of the dilatancy.

During a cyclic loading, the shear stress (i.e. the friction coefficient) can decrease up to 65% after no more than five cycles.

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ACKNOWLEDGEMENTS

The work described in this paper was supported by the Commission of the European Communities though the Science Project n° SC1*-CT91-0659 and by the French GRECO - Géomatériaux.