EXPERIMENTAL SETUPS FOR THE DETERMINATION OF GRANULAR MEDIA BEHAVIOUR

DISPOSITIFS EXPERIMENTAUX POUR LA DETERMINATION DU COMPORTEMENT D'UN MATERIAU GRANULAIRE

Louis MICHIELS [1], Alain HOLEYMAN [1]
[1] *Université catholique de Louvain (UCL), Louvain-la-Neuve, Belgium*

ABSTRACT – Experimental setups used for the study of shear stress in granular materials are reviewed: plane shear, annular and ring shear, inclined plane, heap flow, rotating drum,... There exist many different experiments for the study of shearing in granular materials. Some involve free surface flows while others consider confined shear effects, allowing for a direct comparison with soil failure mechanisms. A comprehensive description of each setup is made, leading to comparisons between different kinds of experimental apparatus. In another section, particular focus is put on the ring shear test, studying existing devices and standards introduced during the evolution of this test method. We consider possibilities it offers for determination of the shearing behaviour in granular media under constant and periodic loading. Finally, putting together advantages of recent advances in ring shear testers, we offer some conceptual views concerning the design of an original testing setup to study rate effects on the shearing behaviour of granular materials.

RÉSUMÉ – Nous passons en revue les dispositifs expérimentaux utilisés pour l'étude des contraintes de cisaillement dans les milieux granulaires : cisaillement plan, deux types de cisaillement annulaire, plan incliné, flux sur un tas, tambour rotatif,… Il existe de nombreuses expériences différentes pour l'étude du cisaillement dans les matériaux granulaires. Certaines impliquent des écoulements à surface libre, tandis que d'autres considèrent des effets de cisaillement confinés permettant une mise en relation directe avec les mécanismes de rupture des sols. Chaque expérience est décrite, amenant à des comparaisons entre les différents types d'appareils expérimentaux. Dans une autre section, nous portons un intérêt particulier au test de cisaillement annulaire, en étudiant les appareillages existants et les standards introduits au cours de l'évolution de cette méthode de test. Nous examinons les possibilités qu'il offre pour la détermination du comportement au cisaillement des milieux granulaires sous sollicitations constantes et périodiques. Enfin, nous assemblons différents avantages de développements récents des appareils de test annulaires pour offrir une vue conceptuelle sur le développement et la conception d'un dispositif expérimental de cisaillement dans l'optique d'étudier les effets de vitesse sur le comportement des milieux granulaires cisaillés.

1. INTRODUCTION

A granular material is a system composed of many macroscopic grains. These grains can have different sizes, densities, shapes and surface roughnesses. Real mixtures of grain are also characterized by a grain size distribution (also called granulometric curve in soil mechanics).

Voids in the granular material are filled with fluid (in most usual applications, air or water) which can have an impact on the mechanic behaviour of the media.

Coarse soils such as sands and gravels can often be considered as granular materials. For finer soils (clay, loam,…), one comes across a transition between granular materials and continuous solids.

Granular matter can be modeled following two classical approaches : the discrete or discontinuous approach and the continuous one. The discrete method considers each grain and the interactions it develops with its surroundings, thus allowing to study strains and stresses on each and every grain in the model. The continuous method considers the granular material as a continuous, unique, deformable mass. It defines equivalent parameters that allow to develop fundamental laws for the behaviour of the material as a whole (thus not considering the discrete particles that compose it).

A distinct attribute of granular media is that they cannot be considered purely as a solid nor as a liquid. Nevertheless, they show fluid-like or solid-like behaviours under different conditions. Many authors have demonstrated that under different parameters (density, shear strain, confining stress,…), a number of regimes appeared with distinct mechanical behaviours.

In order to study those behaviours, several experimental setups have been used. Some go back as far as nearly a century and are widely known and used, but others are quite new in the field of granular matters and therefore far less recognized at this time.

Many of the theories and methods used in granular material studies are not similarly applied to geotechnics or soil mechanics. In the present article, we first analyze different kinds of experiment that have been processed on granular material, in order to see what use could be done of them in the field of geotechnics and more specifically vibrated foundations. Then, we will develop a bit more on the subject of ring shear testers, a very interesting device when it comes to large strains and dynamic soil testing.

2. EXISTING EXPERIMENTAL SETUPS

Existing setups for the study of large strain or continuous shearing in granular media can be divided into two categories : open flow shearing and confined flow shearing. In open flow setups, one of the boundaries is left free of imposed conditions for stresses and displacements (similar to open channel flows in hydraulics). As for confined flows, stresses or displacements are imposed on each of the geometrical boundaries (similar to forced flows in hydraulics).

We will describe the simple shear, annular shear and ring shear, which are commonly used confined flow systems. Then, the open flow systems we will study here are the inclined plane, heap flow and rotating drum.

2.1. Simple or plane shear

In the simple (or plane) shear test, a sample of granular material is sheared between the two horizontal walls of a prismatic cell, moving at different velocities. This allows for a relative displacement of one plate following the horizontal axis and creates an uniform stress distribution along the vertical axis in the sample. A confinement pressure may be applied on the horizontal walls of the cell.

The main advantage of this experimental setup is its simplicity : gravity put aside, the stress distribution involved is continuous and uniform. A disadvantage, however, is the limited course of displacement allowed, due to the size of the cell. Moreover, the small size of the cell implies strong possibilities of edge effects. Only small-scale effects can be observed, in small-displacements conditions. Shearing velocities are also limited. Another problem is the fact that the geometry of the boundary conditions promotes a preferential localization for the shearing plane.

A simple shear test can be used to model soil behaviour under continuous shear of limited scale. It can also be applied to vibrating foundation of piles, although it is not intended to be used in vibratory conditions.

Some variations on the principle of simple shear test have been attempted to model soil-structure interaction (e.g. in Chin & Seidel 2004, where a modified shear test apparatus was developed to study soil-pile interface shearing).

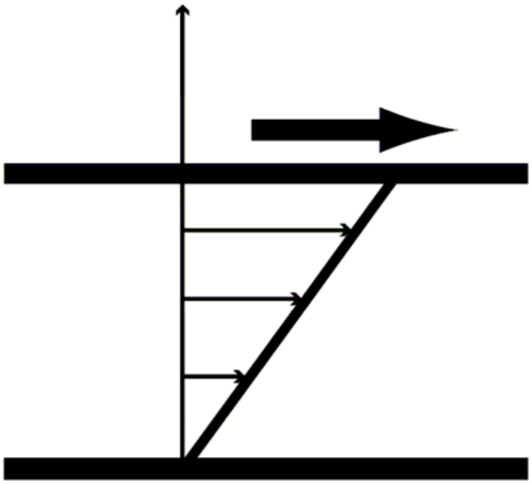

Figure 1. Simple shear (from GDR MiDi 2004)

2.2. Annular shear

The annular shear uses an annular sample of granular material enclosed between two concentric rings. One of the rings is set in rotation while the other remains static or moves at another velocity. Shearing occurs on the width of the sample. Shear stress distribution is not uniform and depends upon position (radius) within the sample.

One advantage of this system comparing with simple shear is the fact that it allows for much larger (theoretically infinite) displacements. A relative disadvantage is the effect of the circular shape on the stress distribution, imposing the use of mean values to globally represent the state of the sample.

Annular shear tests allow to study situations in which displacements are significant. Such cases as landslides and penetration tests can be studied using annular systems. It also allows for the study of soil deformations after failure.

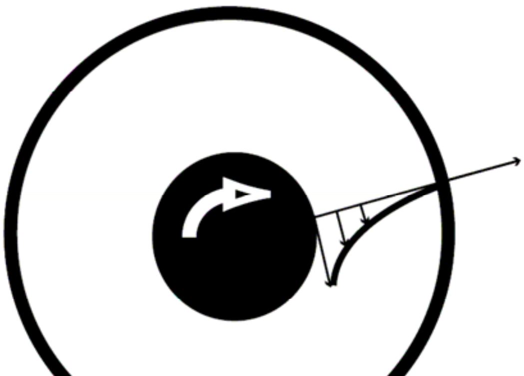

Figure 2. Annular shear (from GDR MiDi 2004)

An annular shear tester has been developed recently at ENPC/LCPC (De Genarro 1999). It is called ACSA (which stands for simple annular shear apparatus) and allows for testing of soil-structure interactions (shearing at the interface between soil and pile with various roughnesses, for example). The ACSA also permits the application of cyclic loading (see figure 3).

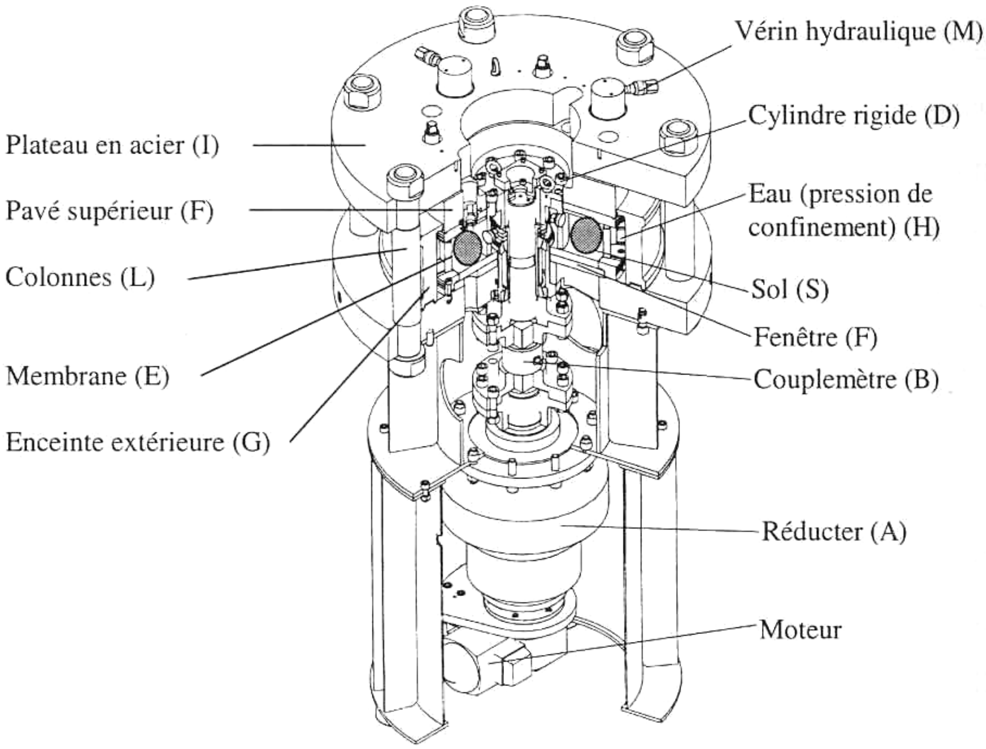

Figure 3. ACSA (from De Gennaro 1999)

2.3. Ring shear

The ring shear test is very similar to the annular shear setup presented before. It also consists in an annular sample of granular matter, contained in an annular cell. The difference lies in the type of applied movement: in the ring shear configuration, the upper plate of the annular cell is set in rotation, while the rest of the cell (lower and both lateral boundaries) remains static (figure 4). Several variations of this geometry have been used since the first applications of ring shear testers.

Shearing is thus induced along the height of the material sample. This test may easily be assimilated to a simple shear test with a periodic boundary condition, as if a long simple shear sample was taken, and one end thereof connected to the other in a circular shape.

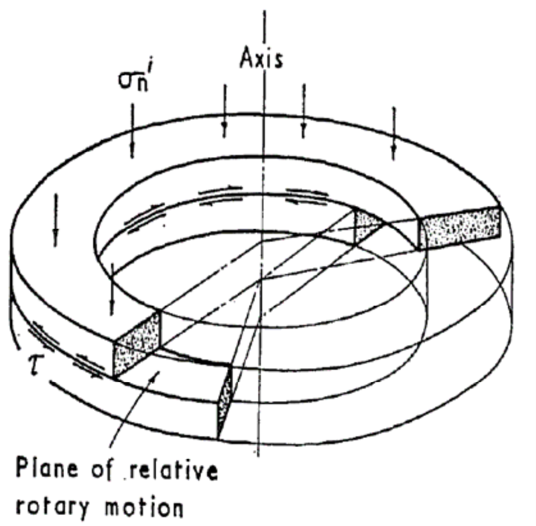

Figure 4. Ring shear testing geometry (from Bishop et al. 1971)

The applications of the ring shear test are quite the same as for the annular test. It is very commonly used to determine the residual shear strength of soils (residual strength is the resistance of the soil after very large deformations have occurred, which is of prime importance for landslides study). Different types and models of ring shear testers have been developed and serve different purposes : ring shear testers are used for powders and grains, sands and other kinds of granular media. They are used to model dynamic and cyclic phenomena as landslides and earthquakes.

2.4. Inclined plane

In this experimental setup, granular matter is deposited in a layer on an horizontal and plane surface. The surface is then inclined to an angle relative to the horizontal. From a given angle, the granular matter will get in movement and endure shearing along the depth of the layer.

As might easily be seen, this situation is comparable to a simple shear setup where the shearing is set off by gravity. However, the dimensions of the shearing surface and thus the possibilities for displacement are larger in this case. An important remark is that, in the present case, the flow occurs under unconfined conditions. Thus, only normal pressure applied is due to the weight of the material and the pressure resulting thereof.

The shear stress profile varies with the height of the granular layer. One can note that the behaviour and characteristics of granular matter in this setup can quite easily be compared with inclined plane flow setups in hydraulics.

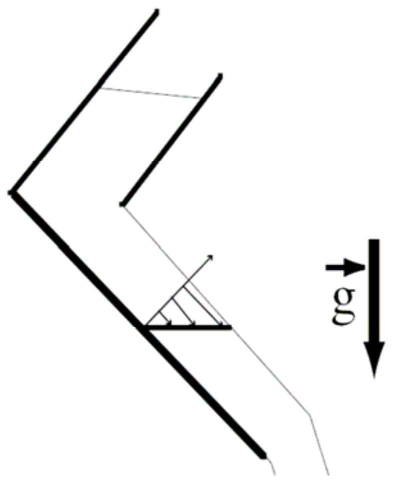

Figure 5. Inclined plane (from GDR MiDi 2004)

2.5. Heap flow

For the heap flow experiment, granular matter is accumulated in a heap on a horizontal surface. Directly above the top of the heap is placed a silo containing more of the granular material.

When opening the silo, the granular matter inside begins to flow on top of the heap. An inclined flow will then occur on the sides of the heap creating a situation similar to the inclined plane setup seen before, but with a bottom plane consisting of granular matter. Thus, the movement of the flowing layer on top of the heap induces displacement of deeper layers in the original heap.

In a situation of uniform and constant flow, the flow velocity will evolve from a maximum on the free surface to a zero-velocity at a given depth in the heap.

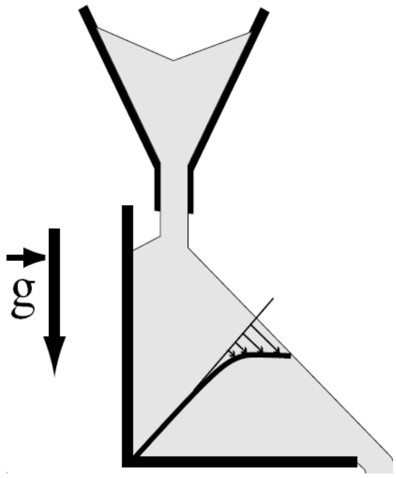

Figure 6. Heap flow (from GDR MiDi 2004)

2.6. Rotating drum

The rotating drum tester, or roll-test, consists in a cylindrical drum partly filled with granular material. When the cylinder rotates around its axis, the grains undergo avalanches when the free surface attains a given angle of inclination.

The resulting shear stress profile is variable from the free surface to the bottom of the cylinder : shearing occurs at the surface, diminishes until a point at a given depth where the shear stress is null and continues in the opposite direction, increasing until the bottom is reached.

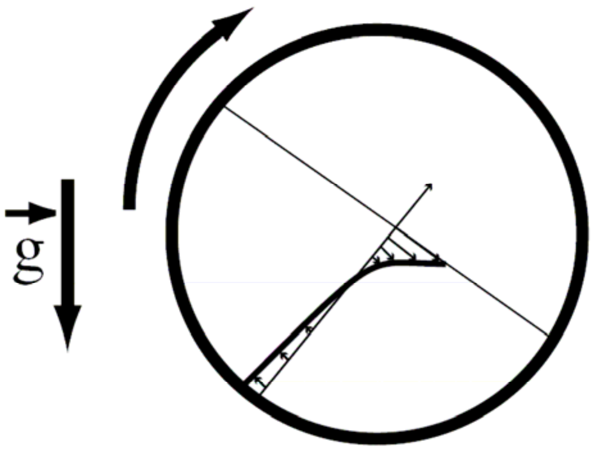

Figure 7. Rotating drum (from GDR MiDi 2004)

2.7. Other testers

Other testers exist, which will not be describe because their use is much less common and they have not been widely studied in the field of granular matter.

3. RING SHEAR – NORMS, STANDARDS AND DEVICES

3.1. Hvorslev, a pioneer

The historical evolution of ring shear tester has been described by Sassa et al. 2004. The ring shear tester was first introduced by Hvorslev (Hvorlsev 1939) at the Vienna Institute of Technology. Hvorslev stated that the main objectives of the shear test were the determination of the maximum shearing resistance, the bond resistance and the velocity of the slow plastic flow before failure, the temporary or permanent decrease of the shearing resistance after failure and the stress-strain relationships and volume change characteristics due to shearing stresses.

Examining the possible shear tests available in regard with these objectives, he concluded that the triaxial test was best suited. However, large displacements are necessary to determine the ultimate shear strength. Such displacements cannot be reached using triaxial tests. Therefore, ring shear testers seemed more adequate in this case.

In the Hvorslev apparatus, the shearing occurs along a predetermined shear plane, at the separation between the upper and lower halves of the cylindrical confining cell (see figure 3). Such predetermined shearing localization allows to ensure that the shearing occurs inside the sample and not between sample and walls. The test occurs under stress-controlled boundary conditions.

3.2. Bishop, Imperial College standard and the modern systems

The original ring shear tester has been further developed and modified by many authors. Bishop (Imperial College, London, UK) was among the first to develop a ring shear tester as it is known nowadays. The shear resistance of the soil is measured by way of direct measurements of the applied torque, the friction stresses (between sample and confining boundaries) and the tangential load

The test is realised under a controlled displacement rate [Bishop et al. 1971] allowing to monitor shear resistance mobilization in the sample. By correctly reducing all possibilities of friction between the mechanical parts of the apparatus, Bishop assured that mechanical errors on the measures of torque and vertical force were limited and inside acceptable limits.

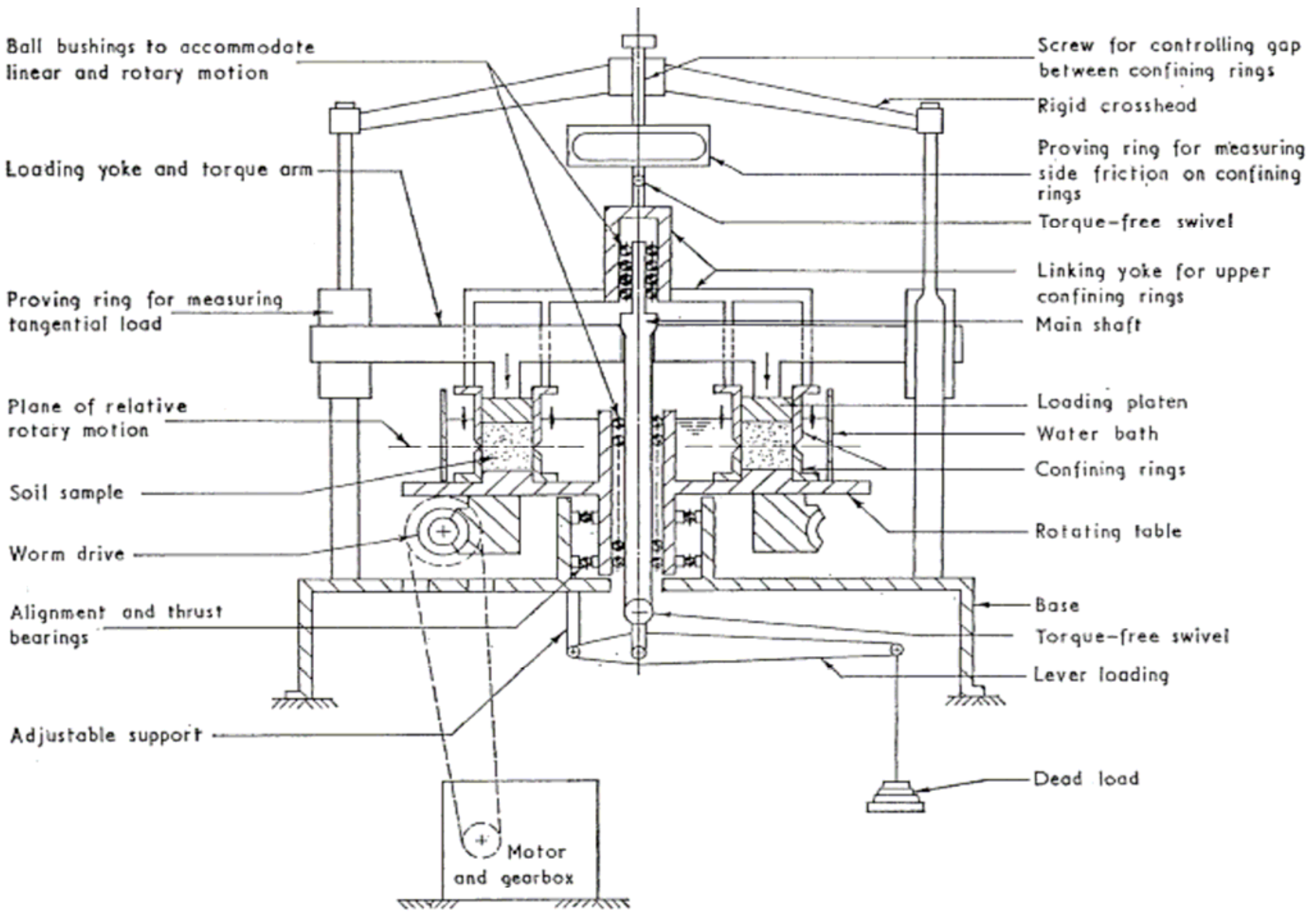

Figure 8. Bishop ring shear tester (simplified section, from Bishop et al. 1971)

Bishop also compared different assumptions that could be made upon the stress repartition on the width of the shear cell. Results showed that any assumption taken did not have a significant influence on the test results (relative variation les than 10 %). Bishop attributed this conclusion to the relative ratio of mean radius to breadth of the sample (approximately 2.5 in Bishop tester). Higher width-to-radius ratios in the sample geometry seem to diminish geometry-dependent errors.

3.3. Bromhead, commercial distribution

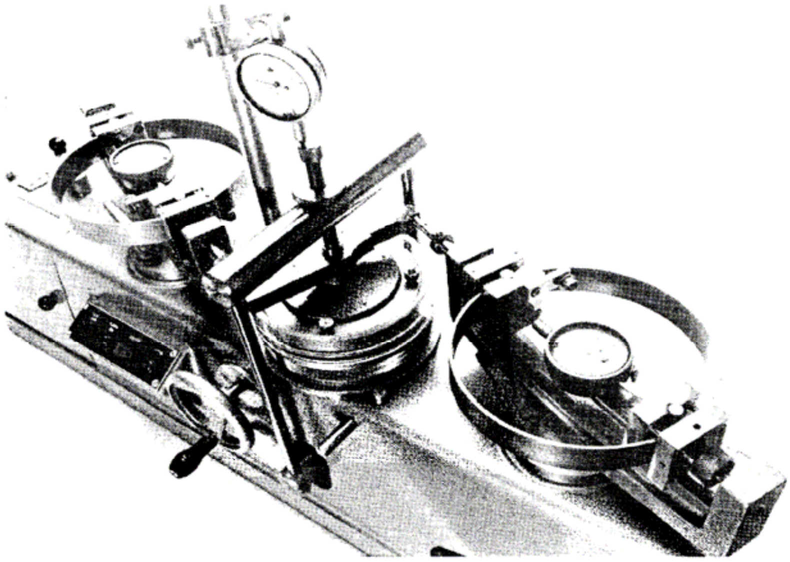

Figure 9. Bromhead ring shear tester, commercial version (from Bromhead 1979)

Bromhead developed a new ring shear apparatus : he changed the confining cell. In this new version of the tester, the material is sheared in the confining cell by ways of moving lateral and lower platens, while the upper platen remains fixed (Bromhead 1979). In Bromhead's model, the thickness of the sample is very small, only 5 mm. It allows large shear rates with drained conditions. This setup was developed and commercially distributed in the form of an automated stand-alone device for soil testing. It has become a widely used standard. Bromhead argues that only remoulded samples can be tested, given that even undisturbed samples would end up being remoulded during the preparation process. However, one could wonder if the relatively low width-radius ratio of the samples used in this tester would not introduce geometry-related errors (variation of shear stress along the radial axis of the tester).

3.4. Other ring shear testers : evolutions

Different variations have been developed on the basis of the standard ring shear testers. Some authors have enlarged the sample radius, in order to minimize the stress profile deformation due to variations along the width of the sample [Kelly et al. 2003]. Other ring shear testers are capable of large shear rate ranges, from very slow shearing to high speed dynamical studies (Sassa et al. 2004, Wang et al. 2004).

Cyclic loads (Sassa et al. 2004), drained and undrained samples, various boundary conditions (with controlled displacements, controlled normal confining stresses, controlled pressure, controlled normal stress – CNS,…) are found amongst recent developments in research laboratories. Kelly et al. developed a large radius shear tester (MKII-SU model, 1 m diameter - Kelly et al. 2003).

In the following table (table I), one can find different models of ring shear apparatus, either commercially-distributed or developed for research and development needs. Figure 10 tries to compare different models, if one considers sample volume and shear velocity as determining factors.

Table I. Comparative study of existing models of ring shear testers

		Geometrical parameters						Shearing parameters			
Ring shear tester	**Reference**	*Φ_{IN} [cm]*	*Φ_{OUT} [cm]*	*H [cm]*	*H/W [-]*	*A [cm²]*	*vol [cm³]*	*max N [kPa]*	*max V [cm/s]*	*max $\dot{\gamma}$ [s^{-1}]*	*max f [Hz]*
Hvorlslev	Hvorslev 1939	5,95	11,95	3,00	0,50	84	253	NC	NC	NC	/
Bishop	Bishop et al. 1971	10,16	15,24	1,90	0,75	101	192	980	NC	NC	/
Bromhead	Bromhead 1979	7,00	10,00	0,50	0,33	40	20	NC	NC	NC	/
DPRI-3	Sassa et al. 2004	21,00	31,00	9,00	1,80	408	3675	500	30,00	3,33	0,5
DPRI-4	Sassa et al. 2004	21,00	29,00	9,50	2,38	314	2984	3000	18,00	1.90	5,0
DPRI-6	Sassa et al. 2004	25,00	35,00	15,00	3,00	471	7068	3000	224,00	14.93	5,0
DPRI-7	Sassa et al. 2004	27,00	35,00	11,50	2,88	389	4479	500	300,00	26.08	5,0
RSTC-01	Schulze technical doc.	10,00	20,00	4,00	0,80	235	942	NC	NC	NC	NC
MKII-SU	Kelly & al. 2003	96,00	104,00	6,00	1,50	1256	7539	1100	NC	NC	NC

Φ_{IN}, Φ_{OUT}	*Internal and external diameters of the sample*
H	*Maximal height of the sample*
H/W	*Ratio of maximal height to maximal width of the sample*
A	*Shearing surface, evaluated from the geometry of the shear cell*
vol	*Volume of the sample, evaluated as the product of the shearing surface by the height of the sample*
max N	*Maximal applicable normal force (confining force)*
max V	*Maximal shearing velocity*
max $\dot{\gamma}$	*Maximal shear rate, defined by dividing the maximal shearing velocity by the height of the sample*
max f	*Maximal frequency of solicitations on the sample, when cyclic solicitation is possible*
NC	*indicates that the data is unknown to the authors*

One may note, on figure 10 (despite the lack of verified values for shear velocities in some testers), that recent shear testers allow for larger speeds of shearing, with larger sample volumes. The MKII-SU tester, for example, allows for a large sample volume. It was not conceived for shear rate effects study, however. Shearing speeds on this tester are very small (max. 100 mm per hour) and shall therefore not be compared with larger velocities for dynamic testers. The DPRI-6 tester seems very interesting : it allows for rapid shearing (more than 2,20 m/s) while taking into account a large (and therefore more representative) volume of test material (more than 7000 cm³). Furthermore, it can perform rapid cyclic tests on drained or undrained soil samples. Some other testers have the same properties, to a greater or lesser extent.

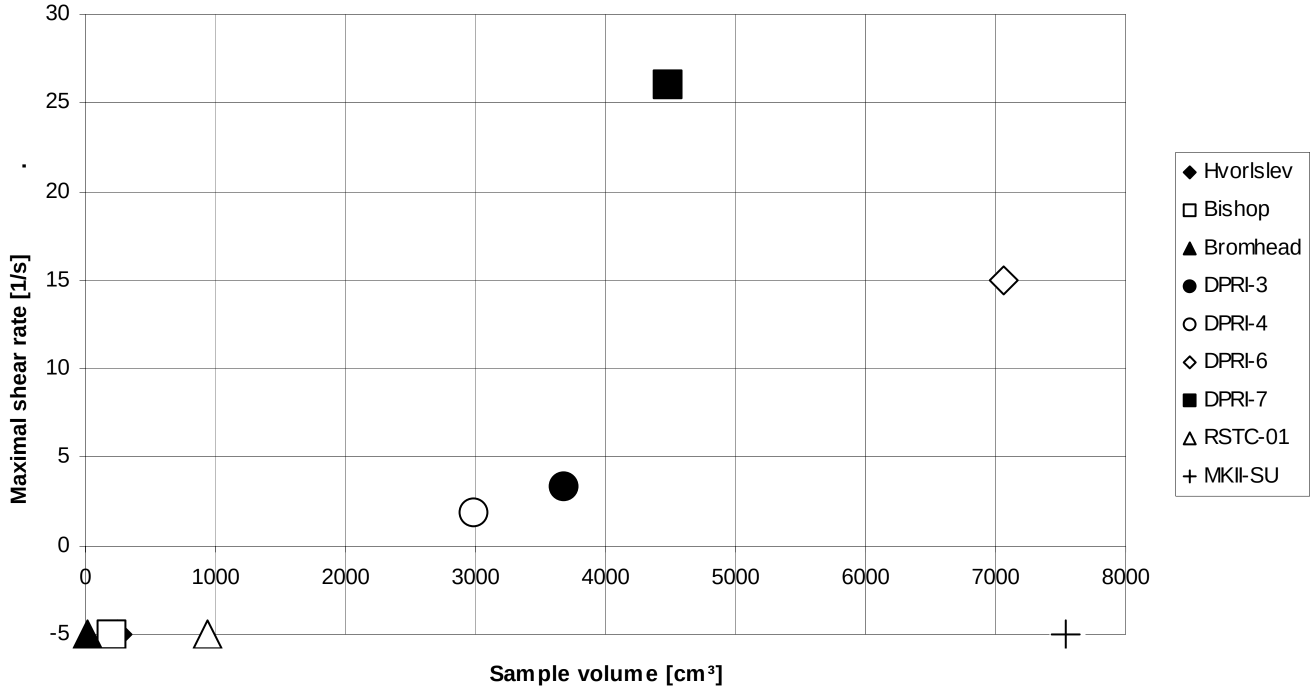

Figure 10. Comparison of ring shear testers – sample volume and shear rate (based on the values from table I)

3.5. Ring shear operating procedure

In order to measure the ultimate shear resistance in a ring shear tester, several steps are necessary. However, by contrast with simple shear test where several samples are necessary to plot a single stress-strain diagram of a soil, in ring shear tests only one sample suffices to get the complete yield locus.

The sample is sheared in two steps (described in Schwedes 2003). First, a “preshear” is applied under a given normal stress until steady state flow is reached (constant shear stress). Secondly, the sample is sheared under an operational normal stress smaller than the “preshear” stress, up to a peak tangential stress. These values (operational normal stress versus peak tangential stress) give the first point of the yield locus. Thereafter, other points can be obtained following the same two-steps procedure for higher normal preshear and operational stresses.

It is important to remember (following Bromhead et al. 1979) that samples used in ring shear tests should always be considered as remoulded. Indeed, even undisturbed soil samples put in place with extreme care in the specific geometry of the shear cell risk being disturbed in the process.

In figure 11, typical curves obtained by way of ring shear test are shown (from Wan & Kwong 2002). Figure 8A shows a yield locus, while figure 8B represents the evolution of shear stress with the deformation until residual shear stress is reached (resulting in a stabilisation of the curves).

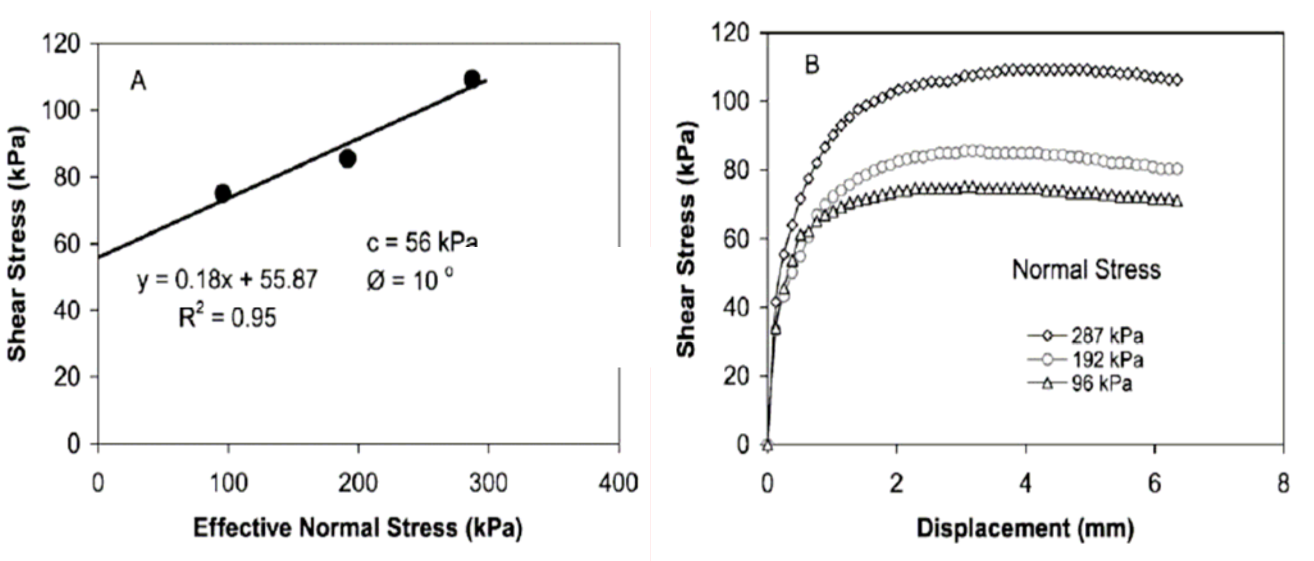

Figure 11. Example of result curves of ring shear tests
(from Wan & Kwong 2002)

Other results may be found in Okada et al. 2004.

4. DESIGN OF AN ORIGINAL EXPERIMENTAL SETUP

In this chapter, the authors will try and discuss interesting features for an original experimental tester. Objectives for this tester would be :

- Measurement of residual shear strength at large deformations
- Evaluation of shear rate effects on the soil resistance
- Dynamical and cyclic effects

From former studies and published results, some important characteristic parameters of ring shear testers can be seen. The maximum speed of the shearing is of importance, since one of the objectives is to try and study the impact of shear rate on the material resistance. Therefore, a large range of range velocities should be available in the new design.

To allow a wide range of velocities, larger geometries could be of interest (along with powerful rotating devices). Larger radius geometries would also permit to reduce geometry-induced errors (variations on the radial axis of the samples) (Kelly et al. 2004).

Ideally, the device would include other interesting features, such as:

- Full variability of confining stresses application
- Drained/undrained testing
- Dynamical and cyclic charge application control
- In-sample measures of pore pressure and stresses
- Imaging techniques for particle tracking and velocimetry (direct optical measures of displacements through transparent wall, along with laser lighting and high resolution cameras)
- Possibilities to perform downscaled penetrometer tests inside the sample (following the horizontal, longitudinal axis) such as full-flow penetrometers (see Randolph et al. 2005 for recent advances), cone penetrometers, etc
- …

5. CONCLUSIONS

In the present article, the authors have described various shear testing devices according to published tests and results. These devices are commonly used in the field of granular materials (understood from the fundamental physics point of view).

Particularly, attention has been attached to the ring shear tester. There seem to be great interest in this apparatus, as it is already being used under well-defined conditions to test particular shearing characteristics of soils (such as shear resistance after large displacements). However, alterations have to be made to the typical devices used for granular matter : larger radii, for example seem interesting, as they allow for larger scale modeling, wider shear velocity range and limited geometry-induced errors. It should also be possible to design an apparatus that could provide high velocities while using large samples.

Obviously, much work needs to be done for the design and production of such a tester. Nonetheless, it seems that it would be very useful for the study of soil behaviour under dynamic charges and the testing of theoretical shear rate dependence laws for soils under shear stress.

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