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Experimental study of sand grains behavior at their contacts with force- and displacement-controlled sliding tests

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Abstract

Discrete element modeling requires the proper quantification of the behavior of grains at their contacts including the normal force – displacement and tangential force – displacement relationships to be used as input for contact modeling purposes. This paper reports on recent advances in soil mechanics experimentation which allowed measuring the grain contact behavior of small sand particles quantifying friction and stiffness with sliding tests of a force-controlled or displacement-controlled type. The particular focus of this work is on the micromechanical behavior of quartz type grains of size between about 1 and 5 mm. A description of the developed micromechanical apparatus at City University of Hong Kong is first discussed and its important different capabilities with previously developed apparatus is briefly reviewed. Subsequently, a limited set of new data is reported and discussed along with a review of recently acquired results published in the literature associated with the contact behavior of quartz sand grains. These sliding tests have covered a wider range of normal contact forces from about 0.5 to 8 N, and the results indicated that, for this range of confining forces, there is not any notable change of the inter-particle coefficient of friction.

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1. Introduction

The discrete element method (DEM) has been a well-established numerical technique in the study of granular materials with particular important implications in geomechanics research and practice. The method has been originally proposed by Cundall and Strack (1979) and a review of the method and its impact in soil mechanics modeling over the past decades may be found in O'Sullivan (2011) and Soga and O'Sullivan (2010).

DEM allows the simulation of virtual samples replicating soil mechanics lab tests which gives the advantage of the continuous monitoring and analysis of the complex material response, that would be almost impossible without the use of a discrete numerical approach (after O'Sullivan, 2011). This has allowed the systematic study of mechanisms which have not been well understood in geotechnical engineering, such as, for example, creep phenomena in granular soils (Kwok & Bolton, 2010, 2013), the complex behavior of binary mixtures composed of soft and hard grains as the solid phase (e.g. Lopera Perez, Kwok, & Senetakis, 2016, 2017), instability of sands (Lopera Perez, Kwok, O'Sullivan, Huang, & Hanley, 2016) or the behavior of anisotropic rocks (Duan & Kwok, 2015; Duan, Kwok, & Pierce, 2015).

An important step in DEM analysis is the estimation of the contact forces at any time step. For these calculations, modelers implement tangential force – displacement and normal force – displacement relationships at the numerical grain contacts. Contact mechanics models have been reviewed in Johnson (1985) with recent updates by

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O’Sullivan (2011). For a realistic constitutive modeling of the grain contact response, which follows the non-conforming type (Johnson, 1985; Mate, 2008), experimental data on real soil grains exploring their behavior is necessary to be produced. However, there has been very limited progress on the topic, particularly due to the difficulties associated with the development of proper experimental apparatus to be used for the purpose of measuring micro-quantities at the contacts of small grains of sand size.

First experimental attempts in measuring grain scale properties of geological materials may refer to the works by Horn and Deere (1962) or Procter and Barton (1974). Cavarretta, Coop, and O’Sullivan (2010), Cavarretta, Rocchi, and Coop (2011) developed an apparatus which could measure friction at the contacts of sand grains conducting relatively high speed shearing tests that could not give information, for example, for the tangential stiffness. Senetakis and Coop (2014) designed a new generation apparatus which could measure friction at the contacts of sand grains conducting much slower tests providing high resolution of the forces and displacements, thus achieving measurements of tangential stiffness at very small sliding paths. Prior to the study by Senetakis and Coop (2014), Cole, Mathisen, Hopkinks, and Knapp (2010) measured tangential stiffness at the contacts of gneiss following the grain-block or grain-grain type, but the surfaces of the materials they tested had been polished, whereas in Senetakis and Coop (2014) or Cavarretta et al. (2010, 2011), the tested surfaces of sand grains were natural.

In this paper, recent advances in micromechanical experimentation are presented with a focus on the development of a laboratory apparatus (Nardelli & Coop, 2016; Senetakis & Coop, 2014) capable to quantify friction and stiffness at the contacts of small size grains. The major focus of this work is the review of these recent advancements with additional information on newly conducted experiments and data recently published in the literature exploring the grain contact behavior of quartz interfaces based on the sphere-sphere (more precisely grain-grain) configuration.

2. A review of the micro-mechanical sliding apparatus

The micromechanical sliding apparatus used in the experiments has been developed at City University of Hong Kong. This apparatus allows the study of the contact behavior of soil grains of size, typically, between about 0.5 and 5 mm. Previous works by Senetakis, Coop, and Todisco (2013a, 2013b) and Senetakis and Coop (2014) have described in details the apparatus and its performance testing reference grains (chrome steel balls) and quartz sand grains. Recently, modifications of the apparatus by Nardelli and Coop (2016) led the establishment of higher quality sliding tests of a displacement-controlled type, whilst in the previous studies investigating friction and stiffness at very small displacements by Senetakis et al. (2013a, 2013b) or Senetakis and Coop (2015), tests of a force-controlled type were more adequate to produce high quality results at very small sliding displacements, below about 2–5 μm.

A schematic view of the apparatus is given in Fig. 1 and a close-up view of the apparatus is provided in the image of Fig. 2. The apparatus is composed of three major parts: (i) The horizontal system in the direction of sliding (tangential

Fig. 1. Schematic view of the micromechanical sliding apparatus of the Soil Mechanics Laboratory, City University of Hong Kong developed by Senetakis and Coop (2014).
direction), which provides the shearing at the grain contacts (ii) The vertical system in the normal to the sliding direction, which provides the vertical confining force to the grains (iii) The out-of-plane horizontal system, which maintains the compliance of the system during the shearing tests (i.e. keeping a stable sliding). After recent modifications of the apparatus, all these three systems are composed of linear micro-stepping motors, load cells and displacement sensors for the control of the experiment and the record of the forces and displacements at the different directions. In the previous studies by Senetakis et al. (2013a, 2013b), the system worked in two perpendicular directions, named the direction of shearing and the vertical direction, while the compliance of the system in the out-of-place direction was maintained by a stiff mechanical system utilizing linear bearings (Senetakis & Coop, 2014). Nardelli and Coop (2016) modified the apparatus incorporating non-contact frictionless displacement sensors (Fig. 3) of a resolution equal to 0.01 μm, which allowed more consistent sliding test results to be produced with greater resolution of the displacements. This is because the initial design by Senetakis and Coop (2014) used the free armature-type linear variable differential transformers (LVDTs) which had a resolution of 0.1 μm. The free armature-type LVDTs could lead to slightly less repeatable results which was largely due to some friction produced by the sensors during the experiments. For this reason, careful calibrations prior to a given test should be conducted with this previous configuration (Senetakis & Coop, 2014). In addition, the modification of the apparatus allowed the control of the humidity during the experiments. Modifications of the mechanical parts of the apparatus increased its stiffness which may allow sliding tests to be conducted at greater normal loads.

Digital micro-cameras are used for the better alignment of the grains at their contacts prior to the shearing tests as well as the record of the experiments. Note that the apparatus is more capable of testing grains applying a vertical confining force (normal force) between about 0.5 and 10 N. This is because the expected developed normal forces at the contacts of soil grains for current engineering practice may be of low magnitude, typically below 5N (Barreto, 2009). As described by Senetakis and Coop (2014), brass mounts and wells are used for the placement of the grains, and superglue is used to fix each grain on the mount.

Senetakis, Coop, and Todisco (2013a) investigated the coefficient of friction at the contacts of quartz grains of Leighton Buzzard sand (LBS). They could produce high quality results at very small displacements, typically below 2–5 μm of sliding, investigating the contact tangential stiffness and the friction on the onset of a steady state sliding through force-controlled tests. A difference of this system in comparison to a previous design of a similar apparatus by Cavarretta et al. (2010, 2011), is that the new design allowed the conduction of sliding tests without the occurrence of stick-slip and because of the high stiffness of the system, the grains could be aligned close to their apexes (i.e. apex-to-apex contact) prior to shearing (Senetakis & Coop, 2014). A typical image of sand grains during their alignment, prior to the conduction of a sliding test, is given in Fig. 4. The apparatus developed by Cavarretta et al. (2010, 2011) was more flexible and necessitated the initial alignment of the grains to be implemented with a small angle without apex-to-apex positioning. For the system developed by Cavarretta et al., the apex-to-apex alignment of the grains would not lead to a stable shearing or good

![Image of the apparatus with the supporting digital micro-cameras for the alignment of grains and record of the tests (after Nardelli & Coop, 2016).](image-url)
quality resolution of forces and displacements at the initial stage of the shearing tests. Thus, the behavior of the inter-particle friction could be captured at relatively larger displacements by Cavarretta et al. (2010, 2011) without information at very small sliding paths which would be necessary to measure the inter-particle sliding stiffness. The new design by Senetakis and Coop (2014) allowed measurements of the tangential stiffness at the grain contacts to be carried out since the newly developed system could measure the sliding behavior at shearing paths of less than 2 μm with a satisfactory resolution of the developed forces and displacements. As described in the studies by Senetakis, Coop, and Todisco (2013b) and Senetakis and Coop (2015), the grain contact stiffness in the tangential direction degrades rapidly and that after the completion of a horizontal displacement of a few microns, the stiffness is zeroed and the sliding reaches a steady state. These findings were aligned with the previous work by Cole et al. (2010). Thus, it was necessary for this type of experiments to develop an apparatus that would allow the initial alignments of the grains to be apex-to-apex. With the recent modifications of the apparatus, the high resolution of the tangential force and sliding displacement could be implemented at even smaller displacements, which made it feasible to conduct tests of a displacement-controlled type rather than force-controlled type. This would allow a more systematic and quantitative study into sliding rate effects on the inter-particle friction and tangential stiffness which might not be the case of sliding tests of a force-controlled type.

3. Typical plots of tangential force – displacement at the contacts of quartz sand grains

In the previous studies by Senetakis et al. (2013a, 2013b), sliding tests of a force-controlled type in the direction of shearing would allow high quality data to be produced at very small deformations which provided
measurements of both friction and stiffness. Experiments of a displacement-controlled type conducted by Senetakis et al. (2013a) and Senetakis and Coop (2014) would be more adequate for the steady state behavior to be captured without providing useful information at sliding displacements below about 1–2 μm, which means that the inter-particle coefficient of friction could be measured but not the tangential stiffness. With recent upgrades of the micromechanical apparatus, as mentioned previously, the system can perform under displacement-controlled tests in the shearing direction capturing forces and displacements before the steady state sliding is reached (Nardelli & Coop, 2016). A typical plot of a displacement-controlled type sliding test from recent experiments conducted by the authors on quartz type grains is given in Fig. 5. These data corresponded to a pair of quartz sand grains (Leighton Buzzard sand) of about 1–2 mm in size. The test was conducted under the application of a vertical force of 1 N and the velocity of the experiment in the shearing direction was equal to 60 μm/h (=0.06 mm/h). This pair of grains was tested in a fairly dry state under room temperature and humidity of about 60%.

Note that, as described by Senetakis and Coop (2014), the analysis of the results should be conducted in a way that from the horizontal and vertical forces (F_h and F_v respectively), the tangential and normal forces are computed based as well on the record of the deflection of the particles in the vertical direction. This implies that there is a rotation of the axes from F_h and F_v to F_T and F_N during the experiment, where F_T and F_N are the tangential and normal forces, respectively. The corresponding formulae for this analysis were given by Senetakis et al. (2013a) and Senetakis and Coop (2014). However, for relatively small vertical and horizontal displacements and the assumption of spherical grains with an apex-to-apex initial alignment, a good approximation during the analysis of the data is that F_h = F_T and F_v = F_N.

As shown in Fig. 5, the steady state sliding is reached after a displacement of about 30 μm, after reaching a peak state (i.e. peak tangential force) at about 10 μm of sliding. These observations are aligned with the reported trends by Senetakis et al. (2013a) with experiments of a force-controlled type on the very similar type of grains. Because the normal force for this test was equal to 1 N, these data demonstrate that the coefficient of inter-particle friction, which is given from the ratio of the tangential force over the normal force, is relatively small for this test, equal to 0.22 approximately during the steady state sliding.

4. Typical plots of tangential stiffness – displacement at the contacts of quartz sand grains

Differentiating the tangential force over the sliding displacement as dF_T/ds, where (s) denotes the sliding displacement during shearing, the tangential stiffness, K_T, is computed. Based on this process, the data of Fig. 5 are reproduced in Fig. 6 by means of tangential stiffness against sliding displacement. Note that the tangential (sliding) stiffness reaches zero at a sliding displacement close to 10 μm which means that K_T → 0 beyond the point that the peak tangential force is reached. The initial sliding stiffness for this experiment could be captured at a sliding displacement of about 0.1 μm, whilst beyond a displacement of 0.4 μm, the tangential stiffness started to degrade rapidly. Note that this experiment is of a displacement-controlled type, whilst the vertical force is maintained constant (equal to 1 N for this test) in a force-controlled manner.

5. Friction and stiffness at the contact of quartz grains: a review with new data

A total set of eight experiments was conducted by the authors and the results of the inter-particle sliding friction by means of tangential force against the sliding force are given in Fig. 7. Note that four of these new tests were conducted at F_v = 1 N with a sliding velocity of 60 μm/h. Additionally, a set of four tests was conducted at F_v = 3 N (one test), 6 N (one test) and 8 N (two tests) with a sliding velocity of 600 μm/h. For all these eight tests, the
conditions were fairly dry. In Fig. 7, the data reported by Senetakis et al. (2013a) as well as their proposed envelope with a slope that expresses the average inter-particle friction at the contacts of quartz grains, are also summarized. The new data corresponded to results of a displacement-controlled type and the data by Senetakis et al. (2013a) corresponded to different experiments of a force- or displacement-controlled type. All these tests, as shown in Fig. 7, including previously published data and newly conducted tests, corresponded to vertical forces from about 0.25 to 8 N. In Fig. 8, the new data by means of tangential stiffness against the normal force are plotted along with the previous data and corresponding envelope proposed by Senetakis and Coop (2015). As for the case of Fig. 7, the $K_T$ values from the new tests were based on displacement-controlled sliding tests, whilst the data by Senetakis and Coop (2015) were derived on the basis of force-controlled shearing tests. Note that from the eight newly conducted tests, only the experiments at $F_v = 1$ N have been analyzed by means of tangential stiffness due to the relatively high speed of the tests at greater normal loads, which did not allow high quality measurement of the inter-particle stiffness for this set of tests. For the data in Fig. 8 by Senetakis and Coop (2015), $K_T$ was computed at a sliding displacement of about 0.5 μm. For the new experiments, two different sets of data are plotted in Fig. 8; one set corresponded to a sliding displacement of 0.5 μm and the second set of data corresponded to 1 μm of displacement. Note the slightly lower values of $K_T$ when the stiffness is defined at 1 μm of displacement and that there is a good agreement between the measured stiffness from the two different types of tests (i.e. force-controlled vs displacement-controlled sliding tests). It is noticed that both force- and displacement-controlled shearing tests may be useful in terms of studying the inter-particle behavior at the contacts of grains but perhaps, for a study of rate effects, displacement-controlled sliding tests would be more adequate since the sliding velocity may be a key parameter in modeling creep at the grain scale (Kwok & Bolton, 2010). This sliding velocity is expressed in terms of mm/h for a displacement-controlled test, but a force-controlled test can give a direct measurement of the grain contact behavior in terms of N/h.

6. Conclusions

The study reported on recently acquired data exploring the friction and stiffness at the contacts of quartz grains of Leighton Buzzard sand. The experiments were conducted with a recently developed micromechanical apparatus for which system its basic features and different capabilities in comparison to previously developed apparatus were briefly reviewed. The friction at the contacts of the grains was found relatively small, similar to the reported results in the literature. The tangential stiffness was quantified based on tests of displacement-controlled sliding tests and the results were aligned with previously published data which were conducted in a force-controlled manner. Particularly, a set of experiments conducted in a range of vertical forces from 1 to 8 N, gave values of the inter-particle coefficient of friction in a range of 0.16–0.25. These data are located on the upper limit of the results presented recently in the literature for Leighton Buzzard sand quartz grains. Extending the sliding experiments at normal loads up to 8 N in comparison to previously reported data, the data analysis did not indicate any notable effect of the normal load on the inter-particle coefficient of friction.
Conflict of interest

The authors note that no conflict of interest exists.

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