Advanced Powder Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Advanced Powder Technology

journal homepage: www.elsevier.com/locate/apt

Original Research Paper

Experimental and numerical study of granular medium-rough wall interface friction

Khadija El Cheikh [a,b,*], Chafika Djelal [a], Yannick Vanhove [a], Patrick Pizette [b], Sébastien Rémond [b]

[a] Univ. Artois, EA 4515, Laboratoire de Génie Civil et géo-Environnement (LGCgE), Béthune F-62400, France

[b] IMT Lille Douai, Univ. Lille, EA 4515 – LGCgE – Laboratoire de Génie Civil et géoEnvironnement, département Génie Civil & Environnemental, F-59000 Lille, France

ARTICLE INFO

Article history:
Received 24 April 2017
Received in revised form 11 July 2017
Accepted 23 October 2017
Available online xxxx

Keywords:
Granular medium
Shear
Friction
Rough wall
DEM

ABSTRACT

Wall roughness plays a crucial role in granular medium - rough wall interface friction. In this study, an experimental device has been designed to study the influence of boundary conditions, more specifically wall roughness, on the behavior of sheared granular medium. The study is based on use of an analog model, and consists of simulating roughness by means of notches and grains in the medium by monodisperse beads and on use of a numerical model based on the discrete element method. The test protocol entails displacing at fixed speed notched rods under confined granular medium. Movement of the beads layer near the rods as well as friction of the beads against the rods are both studied herein. Results indicate that the parameter controlling friction at the granular medium - rough wall interface is primarily the depth of beads embedment in surface asperities. The objective of the associated numerical modeling is to supplement the experimental results.

1. Introduction

Whether in natural form like agricultural products (e.g. rice, corn), sand or aggregates used in concrete production or in a more elaborate form like bitumen, bricks or pharmaceutical powders, granular media are essential to our environment. The geometric and mechanical characteristics of the grains composing these materials are highly diverse, as are the loads potentially acting upon these media during the phases of fabrication, transportation, storage and/or use.

Literature offers valuable information towards an in-depth understanding of the statics and dynamics of granular media, as obtained through both physical experimentation and numerical simulations [1–7]. When studying their flow, granular materials were found to rub against a surface that can be a substrate formed by grain assemblies (avalanche) [8,9] or else a wall (grain flow in a silo) [10–12]. Most research conducted on the rheology of granular media imposed a non-slip condition near the wall. This condition is fulfilled by bonding grains of the same size as mobile grains onto the wall [4]. In this case, the influence of wall roughness on granular medium behavior is not being studied. Nonetheless, an understanding of the phenomena involved at the rough wall contact may provide information on the bulk-related behavior of the granular medium.

A conventional approach to reproduce the phenomena that may occur at the granular medium - rough wall interface is by developing experimental devices in the laboratory. Such experiments may be carried out on model materials, in most cases composed of glass beads. For such a study, the numerical modeling could be a complementary approach to explain physical phenomena from microscopic information that is either difficult or impossible to measure experimentally. To simulate the granular assembly, two numerical approaches are mainly used: a continuous medium [13,14] where the medium is described by finite elements or the use of discrete elements by individually modeling rigid grains of the medium [15,16]. Each of these approaches proves to be pertinent and adapted to a given situation. The continuous medium approach is better adapted to studying global behavior. However, when understanding the phenomena inherent in individual grain movements, the continuity hypothesis is no longer acceptable.

This paper focuses on the granular medium-rough wall interface at the scale of grains capable of becoming interlocked in the wall surface asperities, by means of an experimental approach and then contributing additional information through a discrete numerical approach. On the experimental side, a modified plane/-plane tribometer [17] was employed and an experimental device was specially designed in the Civil Engineering Department of

* Corresponding author at: Univ. Artois, EA 4515, Laboratoire de Génie Civil et géo-Environnement (LGCgE), Béthune F-62400, France.

E-mail address: Khadija.Elcheikh@Ugent.be (K. El Cheikh).

https://doi.org/10.1016/j.apt.2017.10.020

Please cite this article in press as: K. El Cheikh et al., Experimental and numerical study of granular medium-rough wall interface friction, Advanced Powder Technology (2017), https://doi.org/10.1016/j.apt.2017.10.020

the IUT-Béthune institution (French regional laboratory LGCgE). Without seeking to replicate a granular medium at scale or the typical roughness of a wall, a simple model was developed based on the following premise: simulate the asperities of a wall by introducing "notches" machined perpendicularly to the shear direction on a rectilinear support (castellated rod), as well as the granular medium by using glass beads of the same dimension. The principle behind this test consists of shearing a granular medium via a horizontal rod displacement. This device enables not only applying a normal pressure on the granular medium and measuring the speed of rough wall displacement, but also assessing the influence of the ratio between bead size and rough wall asperities on friction at the interface. As for the numerical approach, the discrete element method is implemented in order to explain the experimentally observed blocking phenomena.

This paper will initially provide a description of the device, along with the methodology adopted to conduct an experimental test and the measurements. Next, a study on test reproducibility will be discussed. A parametric evaluation of the choice of rod displacement speed will be presented in Section 4. The fifth section shares the results obtained with the experimental approach, while Section 6 is devoted to both experimental test modeling and the additional information derived by discrete numerical simulation. The concluding section will review both the work accomplished and primary results measured.

2. Experimental program

2.1. Experimental device

The experimental device is composed of a rectangular parallelepiped-shaped box (250 mm high by 300 mm long by 80 mm deep) filled with 10 mm glass beads (Fig. 1). The dimensions of this box are imposed by those of both the tribometer stroke length and its space constraints. The observation of beads movements in the three-dimensional configuration is facilitated by a 10 mm beads dimension.

The box has been fitted at its base with an interchangeable brass rod that serves to simulate the asperities of a surface. The upper surface of the granular medium may be left exposed or subjected to normal pressure. A "T"-shaped steel lid with dimensions slightly less than those of the box, to ensure no friction with the box, may be added to the upper part of the medium while simultaneously authorizing dilatation of the latter. This set-up allows simulating the pressures being exerted by the granular material against a wall (e.g. the case of silos). On this lid, masses may be placed to enable varying the normal pressure. The entire assembly is then positioned on the tribometer [17], a device that makes it possible to move the rod at constant speed and measure the force bearing on the rod. In order to mobilize friction, the rod shifts into a translational motion beneath the granular medium. The rod is 600 mm long with a 300 mm stroke length. During rod displacement, the force being exerted on it is measured by a compressive/tensile force sensor placed between the rod and the tribometer auger (Fig. 1). The sensor measurement range covers 2000 N, with an accuracy of ±10 N. The movement of beads in contact with the Plexiglas box walls is filmed with a color camera (at 25 images/s) positioned in front of the box wall.

The height and spacing of the rod notches are selected such that the beads are able to interlock or not between two successive notches. Three configurations were examined, whereby greater or lesser roughness with respect to bead size was chosen (Fig. 2.

- Roughness R1: The beads are unable to completely interlock between two notches, as both the notch height and distance separating two successive notches measure 5 mm. This case represents a roughness of less than the grain size in the medium.
- Roughness R2: Only one bead is able to completely interlock between two notches. The notch height is 10 mm while the spacing separating two consecutive notches equals 15 mm. This case represents a roughness of the same size as that of the grains in the given medium.
- Roughness R3: Two beads are able to completely interlock within a hollow space. Notch height is 10 mm, and the spacing between two notches equals 25 mm. This is the case where roughness exceeds the medium grain size.

Note that In order to reduce the friction between the plate and the lateral walls of the container, the plate width is made slightly smaller than the width of the container (less 2 mm than the width of the container 800 mm) (Fig. 2a).

2.2. Test methodology

In its initial configuration, the medium is composed of an assembly of 6450 glass beads 10 mm in diameter with a mass density of ρ = 2.6 g·cm^{-3}. A box filling procedure has been devised in order to track the shear profile of the medium during the displacement of the rough rod. For this purpose, the beads are introduced in three columns of two distinct colors (Fig. 3). To prepare the initial configuration of three columns, two plastic plates remaining 100 mm apart are vertically placed in the box (Fig. 3a). Next, 2150 beads are inserted into each column in five layers in order to maintain the vertical plates during filling (Fig. 3b). After introducing the 6450 beads, both plastic plates are carefully removed (Fig. 3c). Then the medium is confined (Fig. 3e) and sheared (Fig. 3f).

2.3. Conducted testing

The shear of the granular medium has been studied for various rod roughnesses, imposed rod speeds and levels of confinement

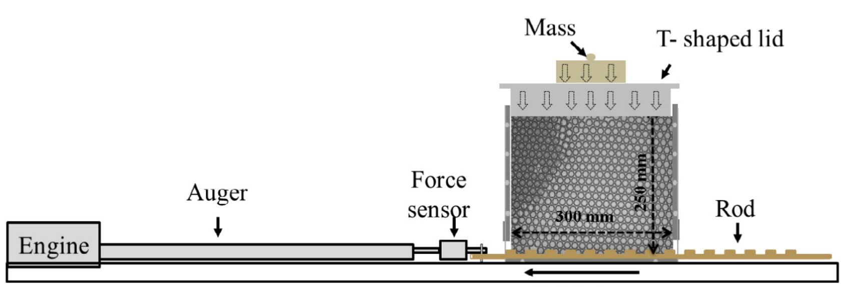

Fig. 1. Experimental device.