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Q1 # Discrete Element study of granular material — Bumpy wall interface behavior

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HIGHLIGHTS

- The shear of spherical particles between two bumpy walls has been simulated with the Discrete Element Method.
- For given bumpiness and confining pressure, the shear velocity does not affect the shear stress.
- For an average interlocking depth lower than 0.25d, effective friction coefficient increases with the increase in interlocking depth and a shear band is observed near the wall. For a critical depth larger than 0.25d, the effective friction coefficient remains constant and the medium is uniformly sheared.

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ABSTRACT

This paper presents a DEM study of a confined granular material sheared between two parallel bumpy walls. The granular material consists of packed dry spherical particles. The bumpiness is modeled by spheres of a given diameter glued on horizontal planes. Different bumpy surfaces are modeled by varying diameter or concentration of glued spheres. The material is sheared by moving the two bumpy walls at fixed velocity. During shear, the confining pressure applied on each bumpy wall is controlled. The effect of wall bumpiness on the effective friction coefficient and on the granular material behavior at the bumpy walls is reported for various shearing conditions. For given bumpiness and confining pressure that we have studied, it is found that the shear velocity does not affect the shear stress. However, the effective friction coefficient and the behavior of the granular material depend on the bumpiness. When the diameter of the glued spheres is larger than about the average grains diameter of the medium, the latter is uniformly sheared and the effective friction coefficient remains constant. For smaller diameters of the glued spheres, the effective friction coefficient increases with the diameter of glued spheres. The influence of glued spheres concentration is significant only for small glued spheres diameters, typically half of average particle diameter of the granular material. In this case, increasing the concentration of glued spheres leads to a decrease in effective friction coefficient and to shear localization at the interface. For different diameters and concentrations of glued spheres, we show that the effect of bumpiness on the effective friction coefficient can be characterized by the depth of interlocking.
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1. Introduction

Granular materials are used in a variety of industrial activities like civil engineering, chemistry, pharmaceutics, food industry .... During handling or conveying, grains rub against walls and create friction. The latter can be the leading cause of many industrial problems because it can hinder motion, create plugs and cause the need for expending extra energy. For all these reasons, friction and interface behavior of granular materials in contact with a rough wall has become of particular interest in many industrial applications.

For example in silos, shear stress acting at the interface between the wall and the granular material can lead to arching [1,2]. The latter can cause problems during the discharge [3–5]. Other processes illustrating the importance of predicting friction between granular material and rough wall are fresh concrete placement into forms and concrete pumping. During these processes, a lubrication layer [6], called "boundary layer" is formed near the wall. The understanding of the mechanisms leading to the formation of the boundary layer is important for the ability to ensure a good concrete placement in forms. As well, the concrete flow in pipe is closely linked to the friction between the concrete and the pipe wall [7]. Previous experimental work has been conducted on fresh concrete by using a plane tribometer. The results showed that many parameters related to the properties of the granular material and the surface characteristics such as roughness play a crucial role in determining the friction at the interface [6]. As well, using another kind of tribometer [8], it has been shown by Ref. [9] that the dynamic angle of friction of fresh mortar against a rigid plane wall increases with the roughness of the wall.

In geotechnical engineering, most structures such as piles and retaining walls are surrounded by soils [10]. The bearing capacity of the structures and the forces transferred from the soils to the structures are affected by the behavior of the soil near the structure [11,12]. The effects of the structure surface roughness on shear band development and shear strength have been widely studied experimentally. The literature suggests rich qualitative data using typical devices such as direct shear test [13–17], simple shear test [18–20] and other devices [21,22]. The results showed that the surface roughness and the mean grain size play a significant role in the shear band development and shear strength [23–25]. Indeed, depending on the surface roughness, a local shear can develop near wall surface, while outside the shear band, the medium is almost not affected [26].

The examples mentioned above show how important it is to understand the mechanisms at the interface between granular materials and rough surfaces. The rheological behavior of granular flows near flat frictional walls has been widely studied in the literature. In the case of chute granular flow, Jop et al. [27] revealed that sidewalls can have a crucial role in the dynamics of surface granular flows. Richard et al. [28] studied the effect of the wall friction on the behavior of granular flows. The results showed that the resultant sidewall friction decreases sharply with depth in granular material, when the depth is above a critical value. In the flowing layers, when the depth is below the critical value, the resultant sidewall friction remains close to the microscopic friction. Artoni et al. [29] proposed a simple scaling law linking the slip velocity to the granular temperature which leads to the effective friction scaling law. In their study on 2-dimensional dense flow of polygonal particles on an inclined chute with a flat frictional inferior boundary, Artoni et al. [30] showed that profiles of shear and solid fraction are nearly unaffected by changes in the particle–wall friction coefficient. Contrary to what happens to bulk profiles, varying the particle–wall friction coefficient does affect the slip velocity which is linear and shifted by slip at the base. The numerical study conducted by Shojaaee et al. [31] on granular material sheared between two flat frictional parallel walls, revealed that walls can lead to shear strain localization in the boundary layer.

However, the interface behavior of granular materials results from sliding and rotating movements of the grains along the asperities of the rough surface [32,33]. Moreover, in some applications (for example concrete friction against pipe walls) the grains size of the medium is of the same order of magnitude than the size of wall asperities. Therefore, depending on the surface roughness, the estimated thickness of the shear band should be scaled by grain size. In those cases, studies at the grain scale of the granular material/wall interface behavior could provide further clarification. However, using experimental devices, it is difficult to explain how the granular behavior develops and how the friction increases/decreases with the surface roughness. The difficulties encountered in experiments, can be overcome by numerical approaches. But the choice of the numerical method depends mainly on the simulated phenomenon. The continuum assumption has been used to model the shear localization for different issues [34–38]. However, to understand from a more fundamental approach the phenomena related to grains movements, the Discrete Element Method (DEM) [39] is an adequate tool. The discrete approach takes into account the discrete nature of the flow. In addition, at each time-step, it provides an access to the contact forces and to the geometrical and physical properties of the system. To model the granular material/wall interface at the micro-scale, the asperities can be described by bumpy walls made of glued particles of the same order of size than sheared particles. Such studies have been conducted either on polygonal [40] or on spherical particles [41–44]

Using DEM, there have been many studies providing relevant information about rheological behavior and kinematic properties of sheared granular materials [45–51]. In sharp contrast to these studies, few discrete numerical simulations have been carried out on shear strength and interface behavior of granular materials close to bumpy surfaces [52,53]. Among the different simulated configurations, the plane [46,50,54–57] and the annular shear [52,58–60] systems are the most studied for the third body concept. In order to ease the bumpiness modeling, most of the results found in the literature are obtained for regular bumpiness made of closed grains similar to the flowing grains (same geometric and mechanical properties) [46,50,54–57]. Until now, the influence of the bumpiness on the development of shear banding occurring near the interface and on the shear stress is still not fully known. Following the relevant numerical studies carried out on plane shear, the main