Powder Technology 279 (2015) 24–32

Contents lists available at ScienceDirect

Powder Technology

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

Characterization of wet granular avalanches in controlled relative humidity conditions

I. Gómez-Arriaran [a,*], I. Ippolito [b], R. Chertcoff [b], M. Odriozola-Maritorena [a], R. De Schant [b]

[a] Dept. of Thermal Engineering, University of the Basque Country UPV-EHU, EUPD Donostia-San Sebastián, Spain
[b] Grupo de Medios Porosos—Facultad de Ingeniería, Universidad de Buenos Aires, Paseo Colón 850-1063, CABA, Argentina

ARTICLE INFO

Article history:
Received 25 November 2014
Received in revised form 12 March 2015
Accepted 31 March 2015
Available online 6 April 2015

Keywords:
Maximum stability angle
Relative humidity
Angle of repose
Granular medium
Hygroscopic equilibrium time

ABSTRACT

This work focuses on the influence of the relative humidity (essentially due to atmospheric conditions) on the many granular media behaviours. To this end, the experimental evolution of the avalanche characteristic angles of continually tilted granular packing was studied for a wide range of relative humidities in very well controlled conditions (between 5 and 90%). The stability angles were measured for fully developed avalanches. The relationship between the relative humidity (ϕ) and cohesion of granular media (directly related to cohesion forces between grains) was then established to identify the different cohesive states of a wet granular medium using a reliable and reproducible testing methodology. Finally, a relationship between the hygroscopic equilibrium time and the stability of the granular packing is discussed.

1. Introduction

Many industrial applications that handle grains are frequently carried out under uncontrolled and variable relative humidity conditions. The environmental conditions during manipulation, storage, and transportation of granular materials can drastically modify their behaviour due to the large fluctuations in the humidity of the environment, which may affect the reproducibility of the results. Southern Brazil, Paraguay, and the Río de la Plata region (Argentina and Uruguay) have a humid subtropical climate, which generally consists of hot humid summers and mild to cool winters.

Despite the systematic dampness in most of practical applications of granular media, few studies have examined "wet" grains; most works are related to the liquid water content between the grains and not the effect of the relative humidity, such as that due to condensation. The relative humidity of humid air, represented by ϕ, is defined as the ratio of the partial pressure of water vapour in the mixture to the saturation vapour pressure at a given temperature and is normally expressed as a percentage. In fact, studies carried out at $\phi = 30$ or 40% (usually called "dry" granular materials) cannot describe the behaviour of real handling or storage conditions, which range from $\phi = 70\%$ to 100%. In previous works [1–5], the influence of the relative humidity and its relationship with the forces that interact between the particles have been studied to show that this parameter can produce a crucial change in quasi-static granular media [6].

In this paper, we recall the storage of moisture in porous media and wet granular avalanches. We then describe our experimental setup and the technique to control the surrounding ϕ. Finally, we show the experimentally measured critical angles of avalanches and the influence on ϕ to identify the characteristic regimes as a function of different cohesive states. Critical angles, measured respect to the horizontal, correspond to the maximum angle of stability (i.e., the angle at which the avalanche is produced) and the repose angle, i.e., the angle formed when the avalanche has stopped. The results of tests and measurements are shown to identify the variables that influence the behaviour of wet granular media. Main conclusions are outlined.

2. State of art

Some authors [2,5,7] have studied the relationship between cohesion and the adhesion forces between grains in a pile when a meniscus is created between grains. These studies have established that the maximum angle of stability varies exponentially with the conditioning time (waiting time in the original reference) of the packing.

However, the measurements were only performed up to $\phi = 45\%$ and did not include the range over which the influence on the stability and cohesion of the granular medium is expected to be important.

Other authors [8,9] have studied piles of granular materials that were previously moistened with liquid water, and this moisture was characterized by the "volume fraction of fluid". In [9,10], the authors noted that the depth of the avalanche plane and the angle of repose positively correlate with the moisture content up to a maximum saturation value, which depends on the size of the grain.

---

[*] Corresponding author.
E-mail address: gomez.arriaran@ehu.es (I. Gómez-Arriaran).

http://dx.doi.org/10.1016/j.powtec.2015.03.050
0032-5910/© 2015 Elsevier B.V. All rights reserved.

The main drawback of this method is that the water is not necessarily homogeneously distributed. The rigorous control of ϕ and hygroscopic equilibrium time is necessary to avoid this inhomogeneity and achieve a uniform distribution of the moisture content in the granular medium at a given hygroscopic and cohesive state. In [11] we have studied the moisture storage mechanism in porous materials and we have found that the size of the voids between grains is similar to the size of the pores of typical porous materials.

Fraysse et al. [12] have carefully controlled ϕ by injecting water vapour in a rotating drum that contained the granular medium. Thus, the control parameter to quantify the moisture content was the relative vapour pressure (P_v / $P_{sat,}$ where P_v: vapour pressure and P_{sat}: saturated pressure), i.e., the relative humidity. They stated that the angle of repose slightly decreased and the angle of maximum stability increased when the moisture content was increased.

The disadvantage of this control technique is its dependence on the injection rate of water vapour into the drum, which increases the uncertainty associated with large deviations in the values of P_v.

In Mason et al. [13], a method of tilting a wet granular packing was used to determine the relationship between the angle of maximum stability and moisture, which is referred to as the volume fraction of liquid.

Other authors [14,15] also identified a relationship between the relative humidity and the characteristic angles of an inclining box filled with 2 mm diameter glass beads. They showed that the size of the packing and its compacity do not influence the angle of repose because this parameter is an intrinsic feature of granular media.

2.1. Moisture in a granular medium

The structure of a static granular media, which consists of solid particles and voids filled with air and water (in liquid or vapour phase), can be assimilated to a porous medium with a solid matrix and pores of different sizes. Thus, the granular medium can be studied as a porous medium from the point of view of the moisture properties.

Two moisture storage mechanisms exist in a porous medium, and therefore, in a granular medium: molecular adsorption and capillary condensation.

Molecular adsorption occurs when the surface areas of the pores or the voids retain water molecules in moist air. In the first phase, the molecules are adsorbed to the walls of the grains, where they can form a mono-molecular layer (Fig. 1a) that increases the moisture content of the granular medium.

This layer is completed at a ϕ close to 20% for the smallest voids; from this stage, the layer thickness then increases with the addition of new molecules that overlap each other, until the so-called multi-molecular adsorption is produced (Fig. 1b) at a maximum thickness of approximately five molecules for $\phi \approx 40\%$.

Beyond $\phi = 40\%$, these layers grow to ultimately collapse, forming a water meniscus that acts as a liquid bridge between the grains (Fig. 1c). This phenomenon is called capillary condensation. As ϕ increases, more bridges are formed in interstitial voids, and isolated regions of liquid water appear in the granular medium. Finally, the medium is completely saturated, and all pores are filled with water.

The dominant moisture storage mechanism depends on the ϕ, but these mechanisms coexist over a large interval of the hygroscopic range. In porous media, the moisture transport properties depend on the moisture content of the material as shown by Gómez et al. in [16], but when the tests are carried out under hygroscopic equilibrium there is no driving force for the diffusive and/or capillary transport.

Different cohesive states can be identified based on these mechanisms of moisture storage because the liquid bridges are at the origin of cohesive forces between grains. Thus, the level of cohesion in the medium will determine these states. The main difference between a dry and a wet granular medium lies in the cohesive force between grains generated by moisture. The cohesion between two spheres as shown in [17] and [18], i.e., the attraction force between two spheres due to a liquid bridge between them, is the sum of the surface tension and capillary pressure in the neck of the bridge.

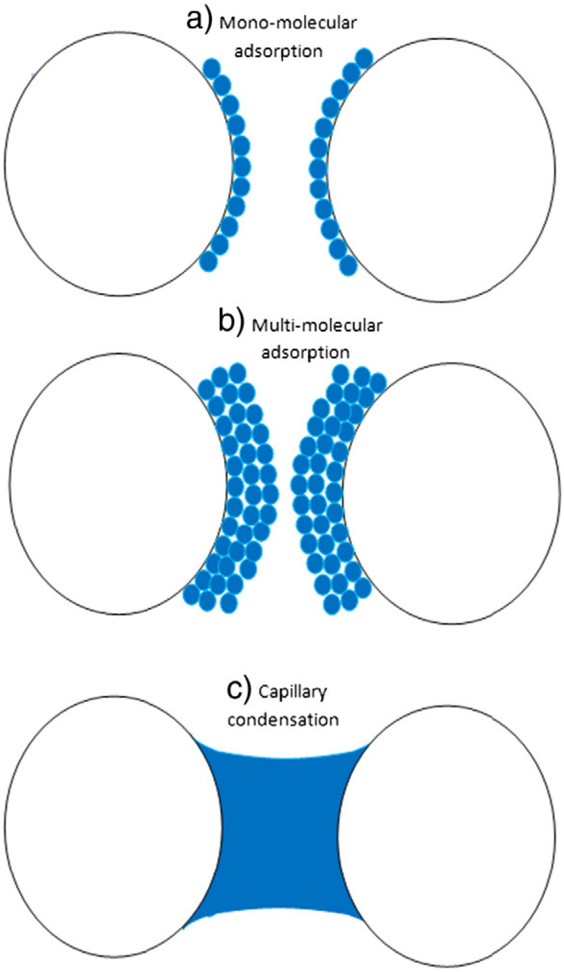

Fig. 1. Schematic of a) the mono-molecular adsorption regime, b) the multi-molecular adsorption regime and c) the capillary condensation regime.

Rumpf [19] proposed a model for determining the cohesion tension in a granular medium of identical spherical grains from the force of cohesion per liquid bridge. This approach is a simple model to estimate the cohesion tension from the liquid bridge force without considering the effect of the distribution in the number and in the size of grains. For a constant packing fraction, the cohesion increases with the average number of liquid bridges and their average strength. Fournier et al. [20] showed that both variables increase with the moisture content.

The packing stability depends on the ϕ of the environment due to these different cohesive states of a wet granular medium. Therefore, we will analyse the variation of the maximum angle of stability (θ_m) and the angle of repose (θ_r) as a function of ϕ in this work.

2.2. Avalanche phenomenon on wet granular media

In the continuum approach, the Mohr–Coulomb criterion describes the avalanche phenomenon in terms of shear stress (τ) and normal stress (σ) modified by the capillary condensation, which creates additional cohesion between grains, resulting in a "normal cohesive stress" in the medium (σ_c) and in a new total normal stress. See [6,21] for more details.

This cohesive stress leads to increments in the angle of maximum stability for a wet granular packing. As the height of the packing increases, the normal stress corresponding to the weight of the pile also increases, but not the component corresponding to the cohesive forces,