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

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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.

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http://dx.doi.org/10.1016/j.powtec.2015.03.050
0032-5910/

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.

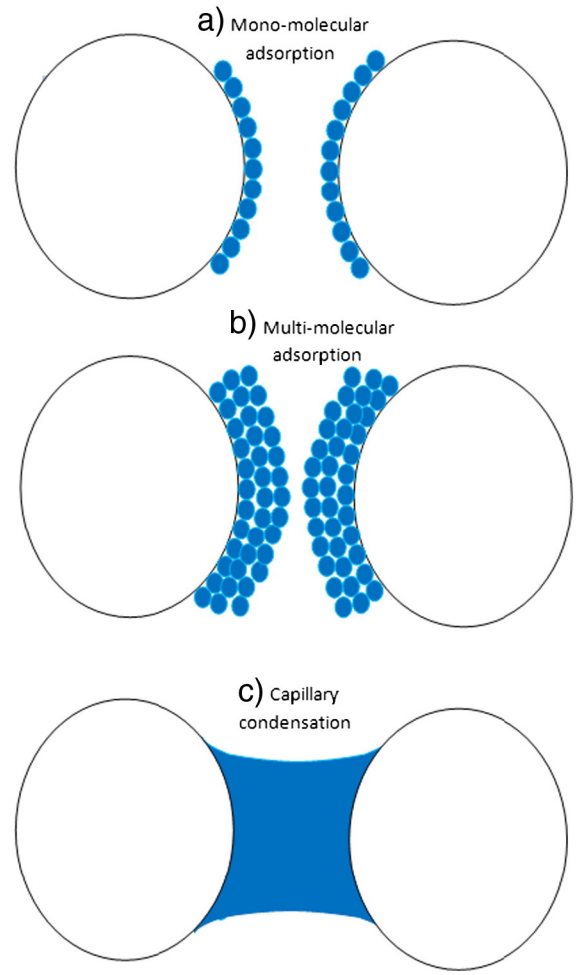

Fig. 1. Schematic of a) the mono-molecular adsorption regime, b) the multi-molecular adsorption regime and c) the capillary condensation regime.

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,

which remains constant irrespective of the size of the pile. Thus, it could be concluded that the depth of the pile does not influence the cohesion; therefore, failure occurs at the base of the pile, according to Mohr–Coulomb criteria, depending on the cohesion degree. The cohesion provided by liquid bridges in the capillary cohesive state is sufficiently strong to ensure that the grains remain up to a high θ_m angle (approximately 90°); thereby, in a fully developed capillary regime, the continuum model and the corresponding Mohr–Coulomb criterion for avalanche can be applied. The continuum approach does not apply to the hygroscopic range or the capillary regimes, where the granular medium is in funicular and pendular cohesive states; in these ranges, the granular medium is more appropriately considered as discrete. In this case, the Albert model [22] considers that a grain from the free surface of the packing breaks out from the irregular geometry formed by the other grains for a given maximum angle. This breakout occurs when an unstable position is reached, at which point the grain will roll down over the others, and the cohesion forces with the grains just below cannot equilibrate it. The final angle is formed when all surface grains attain new stable positions. In this case, the avalanche affects the grains at the free surface of the packing; under this condition, the avalanche is a surface phenomenon. Cohesion due to liquid bridges affects the balance of forces, increasing the angle of maximum stability of the pile.

In both models, continuum and discrete, the cohesive effect of liquid bridges increases the stability of the granular packing: The continuum model predicts that the failure avalanche plan is at the bottom of the packing, and the angle of maximum stability will depend on the size of the packing. For the discrete model the noticeable part of the failure occurs at the surface, although some experiments by Diffusion Light Scattering evidence internal failure [23], and the maximum stability angle is independent of the size of the pile.

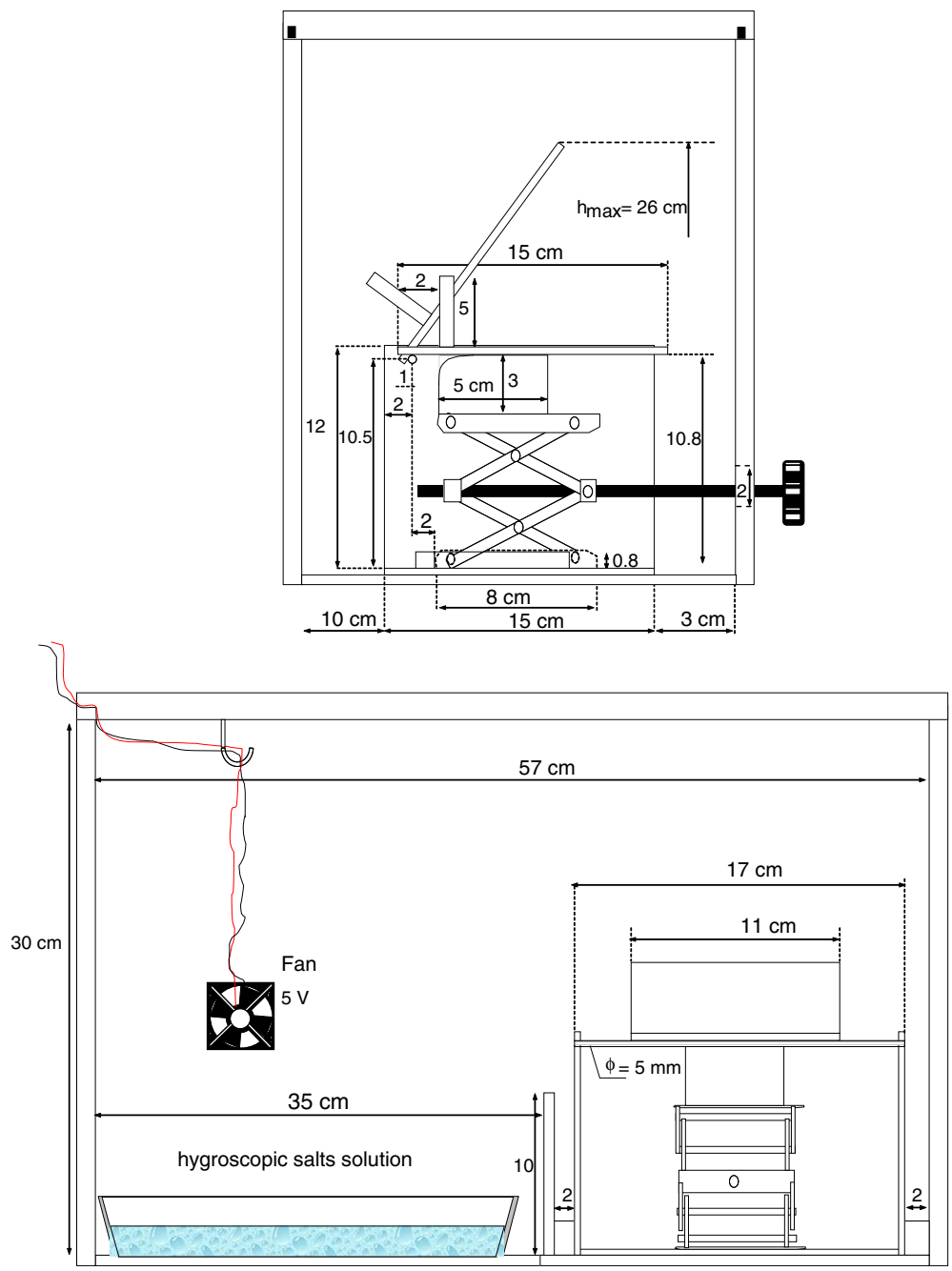

Fig. 2. Schematic of the testing device.

Table 1
Hygroscopic salts and relative humidity used in the experiments.

Hygroscopic salt	CaCl	$MgCl_2$	$Mg(NO_3)_2$	$NaNO_2$	NaCl	KCl	KNO_3	K_2SO_4
ϕ (%)	0%	33%	54%	65%	75%	84%	94%	97%

As we shall see below, our experiments confirm that each model is valid in a specific range of ϕ. Thus, the discrete approach is applicable for the hygroscopic range below 90%, where cohesive forces are lower, while the continuum model is more appropriate for higher ϕ values, corresponding to a fully developed capillary regime in which the moisture content is sufficiently large. In terms of cohesive states, the discrete model is applicable to the funicular and pendular states, while the continuum model is applicable to the capillary state.

3. Experimental setup

To study the characteristic angles of the avalanches for well-controlled humidity conditions, we built two sets of methacrylate chambers with dimensions of $(36 \times 68 \times 36)$ cm^3 and continuous tilting platforms that allow the characteristic angles of the pile to be measured when an avalanche is triggered. We placed a box with dimensions of $6.0 \times 6.5 \times 11.0$ cm^3 in one chamber and a box with dimensions of $5.0 \times 6.5 \times 10.3$ cm^3 in the other chamber. Each box was completely filled with beads, and the free surface was flattened by hitting it with a tool. In each chamber, the box was placed on a pivoting base over an elevating platform. Inside the chambers, it was also placed a tray with hygroscopic salts solution in distilled water.

The grains tested were glass beads with diameters of (0.50 ± 0.04) mm, (1.02 ± 0.03) mm and (2.10 ± 0.04) mm and a density of (2.45 ± 0.15) g/cm^3. The bulk densities were measured by pouring the granular material inside a container of known volume. The material was poured at a constant flow rate from a constant height above the surface of the filled container (constant absolute height). The container was filled up to its rim, and the material was levelled. The density was computed as the ratio between the mass of the material inside the container and its volume. The measured densities were (1.51 ± 0.01) g/cm^3, (1.54 ± 0.01) g/cm^3 and (1.54 ± 0.01) g/cm^3, respectively.

The box was tilted (Fig. 2) by using a platform driven by a shaft. The packing inclination was regulated by the pivoting platform that supported the box. The system was driven by means of an external handle mounted on an axis that crossed one of the walls of the chamber via a small orifice. This device does not significantly disturb the control of the relative humidity in the chamber.

The chambers were sealed in order to maintain the desired relative humidity with a reliable, accurate and simple system based on hygroscopic salts solutions in distilled water, according to [24]. The hygroscopic salts and their respective relative humidities are listed in Table 1.

The air inside was continuously moved using a small fan to prevent stratification.

The relative humidity and dry bulb temperature of the air inside the chamber were registered by capacitive sensors with built-in memory for recording data with an accuracy of $\pm 2\%$ for the relative humidity and ± 0.3 ° C for temperature. The sensors also featured a programmable frequency for reading and recording and transferred the data to a computer. In this study, the data were recorded every 5 min.

After establishment, the desired experimental conditions were maintained for two weeks before starting the avalanche. At this stage, we began to incline the box to initiate the first avalanche; we then measured the angle of maximum stability and repose (Fig. 3). Five minutes later, the angle of inclination of the packing was progressively increased, which resulted in several avalanches. For each successive avalanche, we again measured both angles. The chambers were illuminated from the inside with white light LEDs to obtain sufficient illumination during camera shooting and avoid reflections.

4. Results and discussion

In this section, the results of measurements are presented and analysed.

The inclination angle of the box container and the repose was measured with respect to the horizontal from the pictures obtained after an avalanche was triggered. The angle of maximum stability was then calculated based on these angles, adding the inclination increase between two consecutive avalanches to the last angle of repose.

As mentioned previously, this work aimed to determine the influence of the relative humidity on the characteristic angles in order to estimate the influence on the mass flowing out of the box after the avalanche is produced. To study the influence of the grain size, we tested packing materials consisting of glass beads of three different diameters, 0.5 mm, 1 mm and 2 mm, at different relative humidities ranging from 5% to 90%. However, other parameters play a role in the characteristic angles, such as the packing size, the compaction degree and the hygroscopic equilibrium time. These variables are usually considered to influence the characteristic angles of "dry" granular materials. Nevertheless, we aimed to evaluate how the different humidity degrees in which the pile is immersed change with respect to the dry case. As discussed later, various parameters, such as the equilibration time and the grain size, do not influence the results at low ϕ values.

4.1. Angles of maximum stability and repose

During each test, the number of avalanches obtained depended on the relative humidity at which the material was maintained: the relative humidity positively correlated with the cohesion and stability of the packing, resulting in a smaller number of avalanches. In a later section,

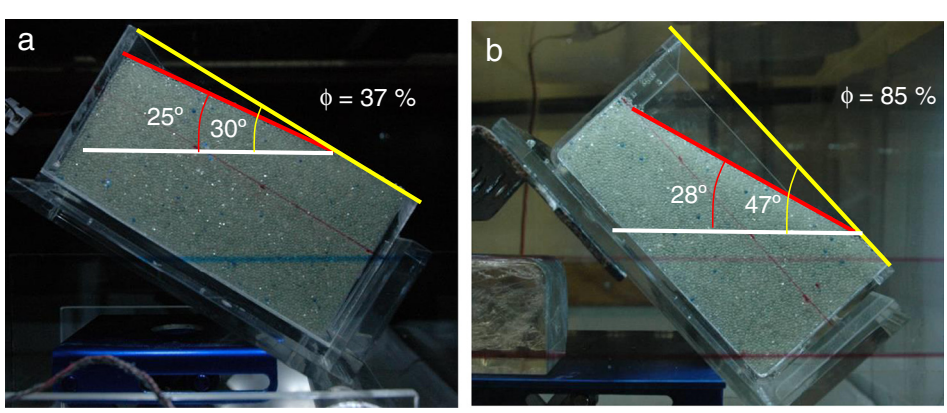

Fig. 3. Images of the angle of maximum stability (yellow) and repose (red) for the first avalanche, grains of 1 mm. a) $\phi = 37\%$, pendular state. b) $\phi = 84\%$, funicular state. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

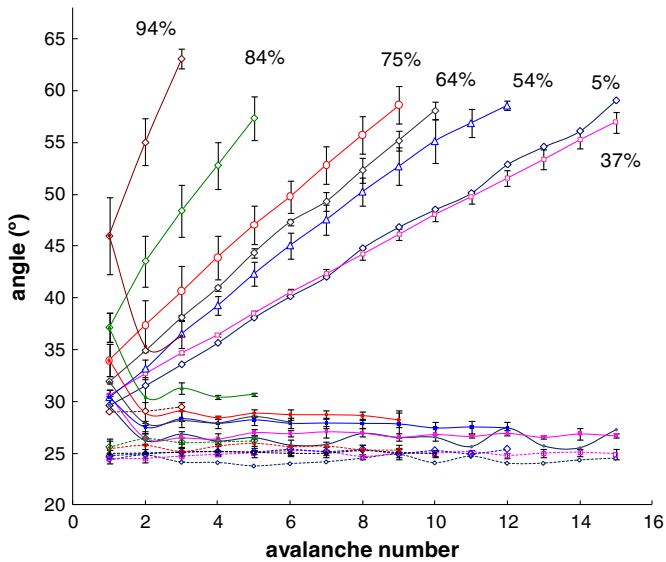

Fig. 4. Characteristic angles as a function of the avalanche numbers for 1-mm grains: maximum stability (full symbols), box inclination (open symbols), and repose (dashed lines). Each colour represents a given ϕ value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

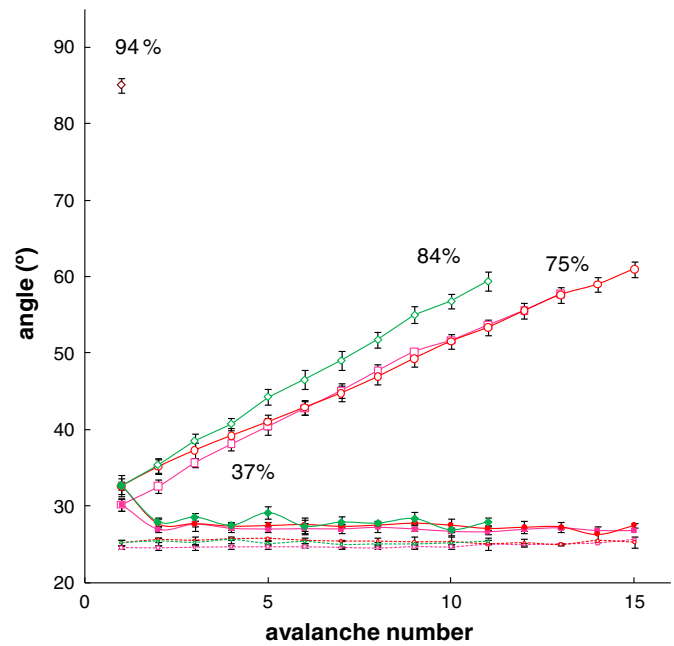

Fig. 6. Characteristic angles as a function of the avalanche numbers for 0.5-mm grains: maximum stability (full symbols), box inclination (open symbols), and repose (dashed lines). Each colour represents a given ϕ value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

we will analyse the effluent mass after each avalanche and its dependence on ϕ.

In Figs. 4, 5 and 6, we have plotted the average characteristic angles (over five equivalent experiments) θ_m and θ_r (dashed) of measurements for grain diameters of 1, 2 and 0.5 mm, respectively.

In all cases, the number of avalanches inversely correlated with ϕ. Thus, 15 avalanches were obtained for low relative humidities ($\phi = 5\%$ and 37%), whereas only one avalanche (0.5 mm grains) and three avalanches (2 mm grains) were obtained for high relative humidity conditions ($\phi = 94\%$).

We observed that the angle of repose was almost constant for all avalanches and slightly dependent on the relative humidity (see Figs. 4, 5 and 6). Furthermore, the maximum stability angle remained approximately constant after the first avalanche. Indeed, the angle of maximum stability was always greater for the first avalanche than the angle of successive avalanches. This phenomenon is due to differences in the time spent before triggering the avalanche. Two weeks were spent before triggering the first avalanche, while successive avalanches were triggered 5 min apart. This finding demonstrates the importance of the hygroscopic equilibrium time, as discussed later in detail.

Fig. 7 shows the difference $\theta_m - \theta_r$ for the first avalanche (squares) and for successive avalanches (circles) for all relative humidities tested. We can observe that the difference between the angle of maximum

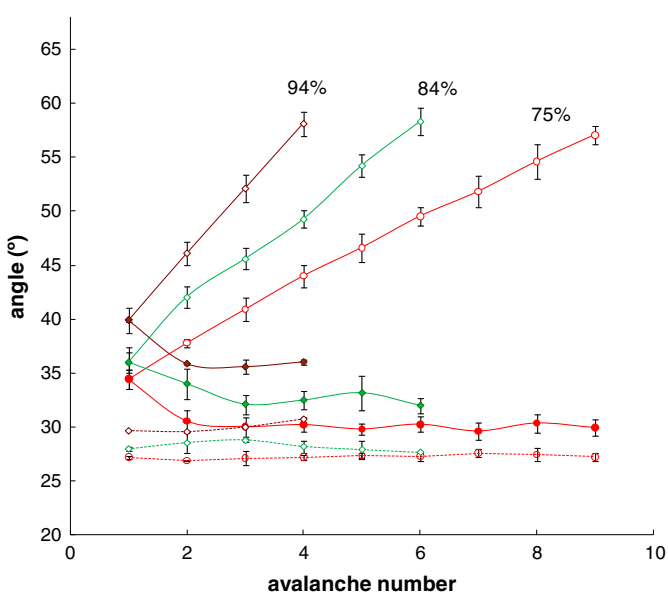

Fig. 5. Characteristic angles as a function of the avalanche numbers for 2-mm grains: maximum stability (full symbols), box inclination (open symbols), and repose (dashed lines). Each colour represents a given ϕ value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

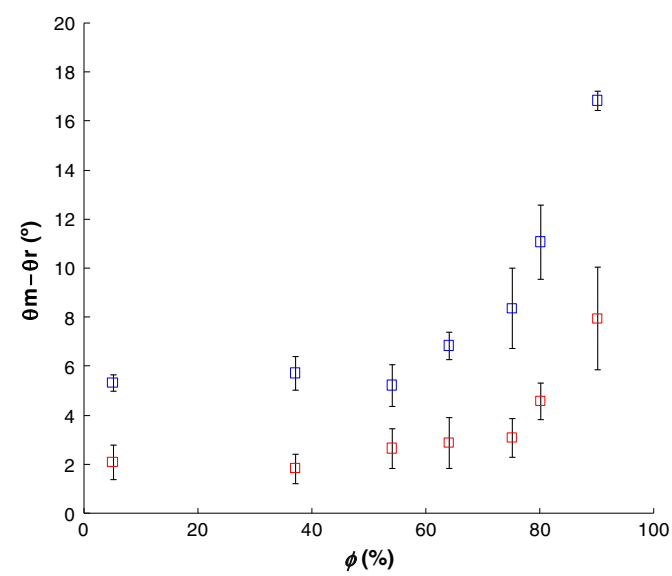

Fig. 7. Difference between the angles of maximum stability and repose depending on the relative humidity for the first (blue symbols) and subsequent avalanches (red symbols) for 1-mm grains, averaged over 5 test values obtained for each case. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

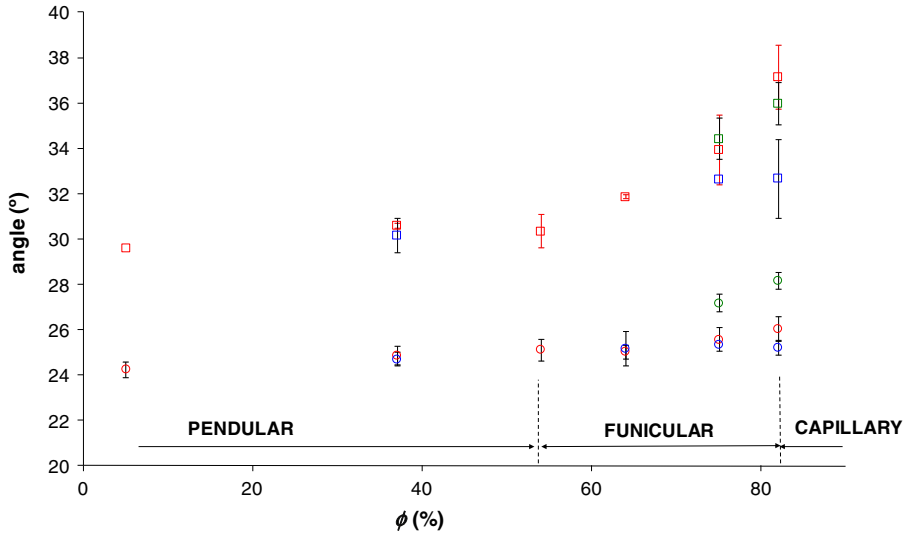

Fig. 8. Maximum stability and repose angles as a function of the ϕ value for d = 0.5 mm (blue), 1 mm (red) and 2 mm (green) for the first (square symbols) and subsequent avalanches (circle symbols). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stability and the repose angle was constant for all avalanches, except for the first one (again due to the equilibrium time between avalanches), and this difference between the two angles positively correlated with the relative humidity following the same variation. Conversely, this difference was nearly constant at low values of ϕ, and exponentially increased at higher values of ϕ; these different behaviours seem to correspond to the different cohesive states of the wet granular medium.

This difference between both angles ranges from 5° (for 1 mm grain size) in the pendular regime to 18° in the wet phase of the funicular state. For a 0.5-mm grain diameter, the difference between both angles also progressively increases from a pendular state up to 25° in the capillary state. The same behaviour was obtained for 2 mm. Thus, we can conclude that the difference between both angles is approximately 5° for the pendular state irrespective of the grain size, suggesting that the characteristic angles are independent of grain size for "dry" conditions and that this parameter only influences the wet condition. Nevertheless, because the behaviour for successive avalanches is the same (Fig. 8), we now compare the angle of maximum stability and repose for all grain sizes used and for the first avalanche.

For clarity purposes, we only show the results obtained up to $\phi = 84\%$ for two cohesive states in Fig. 8. For relative humidities up to 40–50%, the molecular adsorption mechanism of moisture storage in the interstices between grains is dominant, and very few liquid bridges are formed. Therefore, the cohesive forces are not relevant, resulting in almost constant angles of maximum stability and repose. This range corresponds to the pendular state. From $\phi = 40$–50%, the angle of maximum stability increases first exponentially as a result of the capillary condensation evolution in the interstices between grains as the relative humidity increases, providing greater cohesion due to the increment in the number of capillary bridges. At approximately 85%, most of the interstices of the granular medium are flooded with capillary condensed water; relative humidities ranging from 50% to 85% correspond to the funicular state. The upper limit of this range depends on the grain size; the grain size positively correlates with the value of ϕ at which the capillary regime will start.

Our experiments demonstrate that the avalanche occurs somewhere at the free surface of the packing and as a result of mechanical imbalance during the pendular and funicular states; thus, the grains flow

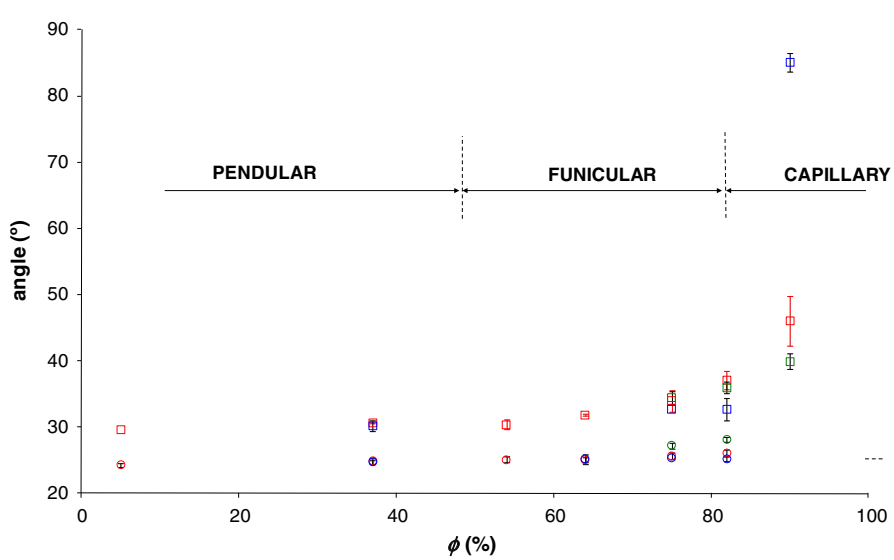

Fig. 9. Angles of maximum stability and repose in terms of relative humidity. Grain diameter of 0.5 mm, 1 mm and 2 mm. Details of the maximum stability and repose angle in the funicular state range, border with capillary state.

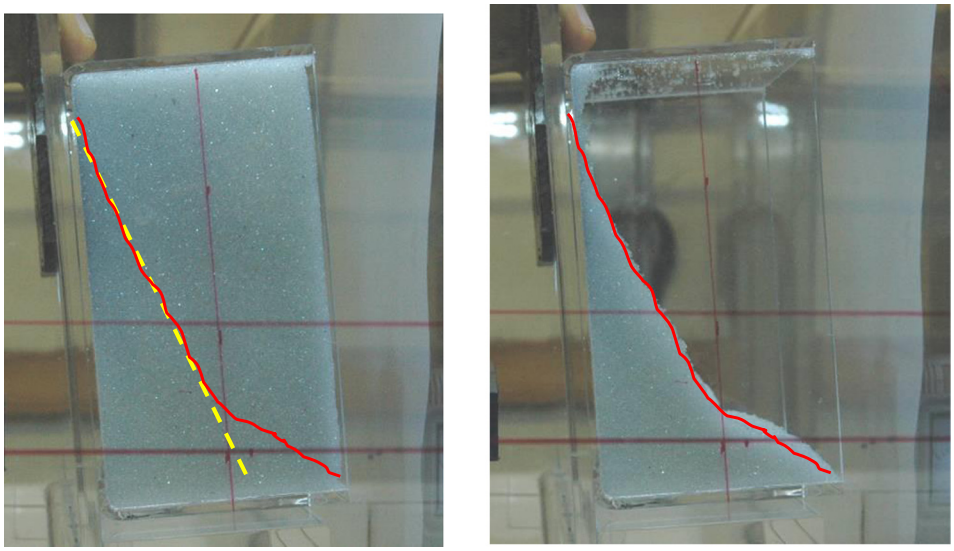

Fig. 10. Packing of 0.5-mm glass beads at $\phi = 94\%$ corresponding to the capillary state before and just after the avalanche occurred. The failure plane is indicated.

out up to a new equilibrium stage (angle of repose) and form a new free surface plane. Therefore, the avalanche phenomenon is a surface phenomenon when the granular medium is in pendular and funicular state, and the cohesive forces are not sufficiently large to consider the medium continuous; it behaves as a discrete medium, as described by Albert et al. [22]. In this regime, the plane of the free surface after the avalanche is well defined, and the angle of repose is easily measured, as shown in Fig. 3a.

In Fig. 9, we show the same variation as in Fig. 8 but for the entire ϕ range and each tested grain size.

Measurements for $\phi = 90\%$ show a sharp increase in the angle of maximum stability for $d = 0.5$ mm. This marked increase indicates the beginning of the capillary state. Indeed, the angle of maximum stability continued to grow as the relative humidity increased due to a more dominant cohesion between the grains (almost all pores are filled with water), which drastically increased the capillary force; as a result, the packing was more consolidated and could be described as a continuum. The angle of maximum stability in this state markedly increased, reaching approximately 85° for this regime. Fig. 10 shows the packed box as well as the failure plan for this scenario. In this case, the avalanche entirely differed from those discussed above: it was not progressive and involved the surface and the bulk, holding the grains together via the capillary moisture content, which suddenly decreased in a block. This finding clearly confirms that the Mohr–Coulomb criterion is more appropriate to explain the phenomenon of avalanches in the capillary state.

The resulting free surface was irregular and hindered the measurement of the corresponding angle of repose after the avalanche, even in the funicular regime. The results obtained for different grain sizes (Fig. 9) show that the limit between the funicular and capillary state shifted to higher relative humidity values for larger grains. More precisely, the capillary state began at $\phi = 90\%$ for grains of $d = 0.5$ mm, yielding $\theta_m = 85°$; the funicular state persisted for $d = 1$ mm at $\phi = 90\%$, it reaching at 95% the capillary state. As mentioned earlier, the angle of maximum stability and repose depend not only on the relative humidity but also on the grain size because the grain size determines the size and distribution of the interstices in which the capillary condensation will occur. Smaller grains are more hygroscopic; thus, they will reach the cohesive capillary state earlier (at a lower ϕ), while larger grain sizes require a higher relative humidity to attain the capillary cohesive state because the pile contains larger pores.

It the funicular state, the characteristic angles are sensitive to the influence of the grain size. In this state, grains larger than 0.5 mm present a larger angle of maximum stability as the relative humidity increases (Fig. 8). In the pendular state, the characteristic angles are independent of the grain size.

Fig. 11 shows the angle of repose as a function of the maximum angle of stability for all grains depending on the relative humidity. We plotted the results corresponding to the first and latter avalanches. As mentioned previously, we confirm the same trend for both cases. Conversely, grain size only influenced the results for higher ϕ values; larger grains provided greater angles of repose; at low ϕ, the influence of the grain size can be neglected and the data collapse.

4.2. Hygroscopic equilibrium time

Previous studies, such as [7], state that the relationship between the angle of stability and conditioning time is exponential. However, this relationship was established only for very low humidity values below 45%. In this range, the granular medium is usually in the pendular state, as we have seen in our experiments.

As we demonstrated above, the angle of maximum stability of the first avalanche differs from those of the later avalanches, which are constant and lower than that of the first avalanche (Figs. 4–6). Prior to the first avalanche, the medium is in contact with the environment for a

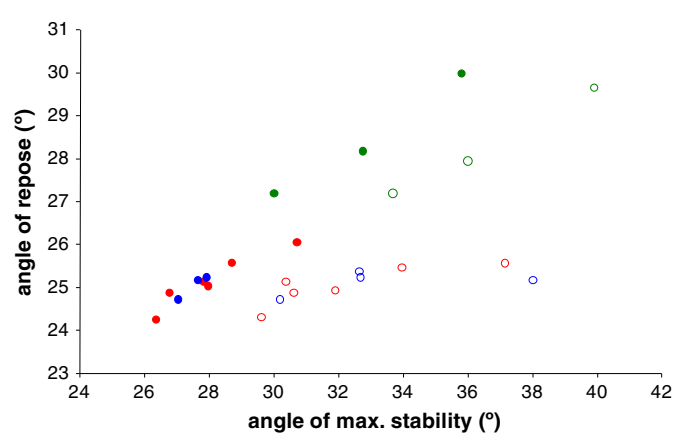

Fig. 11. Angle of repose as a function of the maximum angle of stability for grains of 0.5 mm (blue), 1 mm (red) and 2 mm (green) depending on the relative humidity for the first (open symbols) and subsequent avalanches (full symbols). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

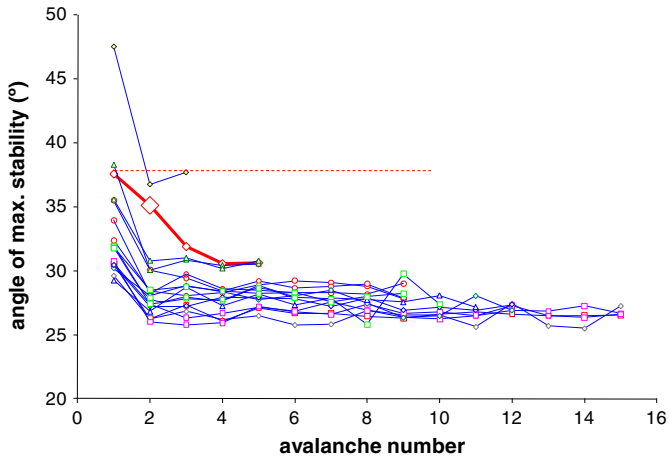

Fig. 12. Angle of repose and maximum stability for 5 min (blue) and 24 h (red) between avalanches for 1-mm grains. The "expected" evolution of the stability angle for different times between avalanches is shown (red dot). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

time long enough to reach hygroscopic equilibrium (two weeks). For later avalanches, the time intervals between two successive avalanches were 5 min.

For all tested relative humidity values, the maximum stability angle decreased for the second avalanche compared to the value obtained for the first avalanche. The angle remained constant after the second avalanche. The angle of repose remained constant for all avalanches, including the first. Thus, this angle is nearly independent of the equilibration time and therefore does not depend on the humidity degree. In fact, results in Figs. 4, 5 and 6 show that the angle of repose slightly increases with the relative humidity from 24° to 27°. Therefore, the angle of repose is more sensitive to the moisture content in the bulk and not that in the superficial layers. Conversely, the angle of maximum stability seems to be a strong function of the humidity and the corresponding liquid bridges in the surface layers of the packing; this is not the only factor, but also the packing history (packing fraction, piling method, walls of the box and geometrical new structure of the surface after the first avalanche occurs) has an influence on the angle of maximum stability. The influence of these variables will be studied in future works.

To examine this phenomenon in more detail, a new test was carried out in which the interval time between avalanches was changed from 5 min to 24 h between the first and the second avalanche for a packing that consisted of grains of 1 mm diameter and $\phi = 80\%$. The result is shown in Fig. 12; we observed that the angle of maximum stability of the second avalanche was larger than that of the same avalanche with a 5 minute equilibration time.

Finally, the "nominal" angle of maximum stability only will be achieved if the granular medium previously retains sufficiently long contact with the environment in order to reach hygroscopic equilibrium; furthermore, all liquid bridges in the granular medium must have been formed according to the surrounding relative humidity. This contact time can be called the "hygroscopic equilibrium time".

5. Conclusion

We have stated here that the relative humidity drastically affects the stability of granular media by increasing the maximum angle of stability with the relative humidity, while the angle of repose remains roughly constant. In this work, we have demonstrated how the different mechanisms of storing moisture affect the stability of a granular media that are tilted to produce an avalanche. The experiments were well controlled, and we have essentially explored the entire range of relative humidity.

The behaviour of a granular medium obeys its cohesive state such that the relationship between the relative humidity and the angle of maximum stability is governed by three different regimes that correspond to the cohesive pendular, funicular and capillary states. During the pendular cohesive estate, both angles remain constant with a difference between them of $5 \pm 1°$. Nevertheless, θ_m grows exponentially when the packing is in the funicular cohesive state, increasing to an abrupt maximum value in the cohesive capillary state that allows the medium to behave as a compact mass due to the strong cohesion.

The relative humidity values that define the frontiers between each cohesive state (pendular, funicular and capillary) increase with the grain size; that is, for small grain sizes, the capillary state is reached at a lower relative humidity than for larger ones. The transition from the funicular state to the capillary one then occurs at higher relative humidities for larger grain sizes. In summary, the maximum angle of stability depends on the grain size in the funicular and capillary state and can be neglected in the pendular state.

The concept of a "hygroscopic equilibrium time" was defined as the time for which the granular medium is in hygroscopic equilibrium with the surroundings. Consequently, θ_m will be maximized during this state. This characteristic time depends on the relative humidity, grain size, free surface area, bulk and compaction degree of the packing. A "nominal angle of maximum stability" was defined as the angle at which the avalanche occurs when the medium has reached a given "hygroscopic equilibrium" with the environment. If the conditioning time is shorter, the avalanche will be triggered at a smaller angle compared to the nominal during adsorption or at a larger angle during desorption. Thus, when referring to the characteristic angle of a packing, such as the angle of maximum stability, not only should ϕ be specified, but whether it is the nominal value or whether this value refers to the desorption or adsorption process should also be specified.

The mass displaced was confirmed to positively correlate with the relative humidity in the same way as the angle of stability does when taking into account the different cohesive states. A linear relationship between the angle of maximum stability and mass eviction in each avalanche was also confirmed, and this relationship depends on the shape and size of the packaging.

Acknowledgements

This work was supported by the Basque Government of the Basque Autonomous Community (Spain) and PIP Conicet 1022, and UBACyT funds. The authors wish to thank the Laboratory of Quality Control in Construction of the Basque Country Government and the University of the Basque Country. We appreciate the helpful discussions with M. A. Aguirre and J-P. Hulin.

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