

## Silo Clogging Reduction by the Presence of an Obstacle

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We present experimental results on the effect that inserting an obstacle just above the outlet of a silo has on the clogging process. We find that, if the obstacle position is properly selected, the probability that the granular flow is arrested can be reduced by a factor of 100. This dramatic effect occurs without any remarkable modification of the flow rate or the packing fraction above the outlet, which are discarded as the cause of the change in the clogging probability. Hence, inspired by previous results of pedestrian crowd dynamics, we propose that the physical mechanism behind the clogging reduction is a pressure decrease in the region of arch formation.

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The flow of particles through a bottleneck is prone to spontaneously developing clogs, which are able to arrest the flow and produce a rapid dissipation of the kinetic energy of all the particles in the system. This behavior is observed in different scenarios such as grains discharging from a silo [1], people escaping from a room [2], bubbles passing through an orifice [3] and vehicle traffic in a highway.

Since To and co-workers proposed that the clogging in the discharge of a silo is caused by the formation of arches whose shape can be explained through a restricted random walk model [1], numerous researches have been devoted to this phenomenon [4–10]. From these works, it is rather well known that the main variable that comes into play in the clogging process of spherical particles is the ratio between the outlet size and the diameter of grains. Indeed, for three-dimensional silos, it seems that there is a critical outlet size above which clogging is not possible [4]. For the two-dimensional case, the existence or not of such a critical size remains unresolved [5,6]. In both cases (2D and 3D silos), for a given outlet size, the sizes of the avalanches  $s$  (measured as the number of particles that flow out of the silo before an arch blocks it) display an exponential distribution. This behavior can be understood if  $p$  (the probability that a particle passes through the outlet without forming an arch) remains constant during the whole avalanche [4]. Hence, the distribution of avalanche sizes can be written  $n(s) = p^s(1 - p)$ , where  $1 - p$  is the probability that a particle forms an arch that blocks the orifice. In another work, Helbing *et al.* [10] also obtained an exponential decay of the sizes of the groups of particles escaping from a bottleneck as a result of a random alternation between particle and gap propagations.

Another physical scenario which presents strong similarities with the discharge of a silo is the outflow of pedestrians from a room. Indeed, it has been found that arching of people is also responsible of the flow halt. Nevertheless, contrary to the case of grains in a silo, when the flow of people is interrupted, it can be spontaneously

resumed without an external input of energy. In any case, the sizes of the groups of people escaping from the outlet (bursts) can be measured. The burst size distribution has been found to be exponential if the outlet is sufficiently small whereas it tends to a power law when the outlet becomes larger [2,11].

A practical solution that is commonly implemented to improve the flow in both scenarios, people escaping from a room and the discharge of a silo, is the placement of an obstacle (or insert) just before (or above) the exit [2,12–18]. In the case of the silo discharge, selecting the right insert position and size has been proved to increase the flow rate up to 10% [17,18]. In the case of human crowds, the placement of an insert decreases the transient clogs which are responsible of increasing the evacuation time of a room [2,13,14].

These works have brought substantial advances in the knowledge of particulated flow through bottlenecks, but a deep understanding about the way by which an obstacle affects the clogging is still lacking. In this manuscript we investigate this process in a 2D silo discharged by gravity. When the distance from the obstacle to the outlet is modified, dramatic changes in the clogging probability are observed with no significative alteration of the flow rate or the local packing fraction above the orifice. Instead, we propose that the insert reduces the pressure in the region of arch formation, being this the main cause of clogging reduction.

The experimental apparatus consists on a two dimensional rectangular silo (500 mm high and 200 mm wide) made of two glass sheets separated by a frame of 1.1 mm width. The granular sample—consisting on monodisperse stainless steel beads with a diameter of  $1.00 \pm 0.01$  mm—is allocated between the two glass sheets conforming a monolayer. The grains are poured into the silo along its whole width through a hopper at the top. The flat bottom of the silo is formed by two facing metal pieces, so that their edges define the outlet size  $R$  which in this work is fixed at  $R = 4.2$  mm. The experimental setup used here is like the

one described in [6] with the only difference being that a circular obstacle has been placed above the outlet (Fig. 2). The obstacle is a steel washer (1 mm thick and 10 mm diameter [19]) glued to one of the glass sheets with its center aligned with the center of the outlet. The distance from the bottom of the obstacle to the outlet ( $h$ ) was carefully measured with a precision of 0.05 mm. From now on, the case of a silo without obstacle will be referred to as  $h \rightarrow \infty$ .

After the silo filling, grains start to pour freely from the exit until an arch blocks it. The avalanche size is measured, in number of beads, with a balance at the bottom. A picture of the region near the orifice is taken and analyzed in order to characterize the blocking arch. Then, the flow is restarted by blowing a jet of compressed air aimed at the orifice. The silo is refilled whenever the level of grains falls below a fixed threshold of around 300 mm (1.5 times the width of the silo). Eleven different values of  $h$  were explored, and for each one, around 3000 avalanches (and the corresponding arches) were registered. Additionally, for each obstacle position 12 movies of the region above the outlet were recorded at 1500 frames per second during 4 sec. These recordings were taken in order to analyze the influence of the obstacle in several dynamic properties of the avalanche (flow rate, particle velocities and bulk density of the sample near the exit). For this reason, the recordings were always performed in the flowing regime, and 3 to 4 sec after the beginning of the flow to avoid any possible influence of a transient regime.

Let us start by presenting the experimental results of the avalanche sizes,  $s$ . In the inset of Fig. 1 we show that, regardless of the obstacle position, the avalanche size distribution displays an exponential decay as it was previously found for the silo without obstacle [4]. The

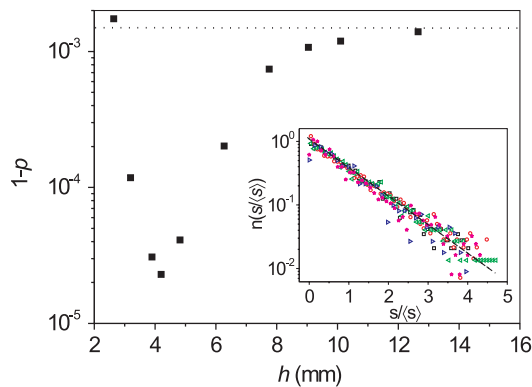


FIG. 1 (color online). Probability that a particle clogs the outlet ( $1 - p$ ) for different insert heights ( $h$ ). The horizontal dashed line indicates the value of  $1 - p$  when  $h \rightarrow \infty$  (silo without obstacle). Inset: semilogarithmic plot of the avalanche size distributions rescaled by the mean avalanche size for  $h = 2.64$  mm ( $\diamond$ ),  $h = 4.82$  mm ( $\triangleright$ ),  $h = 6.27$  mm ( $\triangleleft$ ),  $h = 7.75$  mm ( $\circ$ ),  $h = 12.65$  mm ( $\square$ ) and  $h \rightarrow \infty$  ( $\star$ ). The dashed line indicates the exponential behavior.

difference between the distributions for different values of  $h$ , is the mean avalanche size  $\langle s \rangle$  which is indeed related to the probability that a particle clogs the outlet ( $1 - p$ ) by the equation  $1 - p = 1 - \langle s \rangle / (\langle s \rangle + 1)$  [6].

In Fig. 1 we show the values of  $1 - p$  for different  $h$ . Interestingly, except when the insert is extremely close to the outlet, the clogging probability is smaller than for the silo without obstacle. This result suggests that the obstacle induces in its proximities some kind of modification of the particle flow that prevents arching. Clearly, this effect is enhanced as  $h$  decreases, subsequently reducing the clogging probability. If  $h$  is too low, the clogging probability increases again as a consequence of the development of arches between the obstacle and the silo bottom (top left of Fig. 2). These type of arches were already observed in silos with oblique exits [21] and in pedestrian flows [13]. In the graph displayed at the bottom of Fig. 2 we show—as function of  $h$ —the relative number of arches between the obstacle and the bottom with respect to the total number of registered arches. The increasing of such type of arches for  $h < 4$  mm confirms the hypothesis that the growing of the probability of clogging for small values of  $h$  is a consequence of the development of such structures. Additionally, it follows that for  $h < 4$  mm, the characteristic length which governs the clogging is not the outlet size but the distance between the obstacle and the bottom.

In the following we will try to find the cause for the dramatic reduction in the clogging probability (2 orders of magnitude in the best case) induced by the presence of an obstacle (Fig. 1). The first physical variable analyzed is the

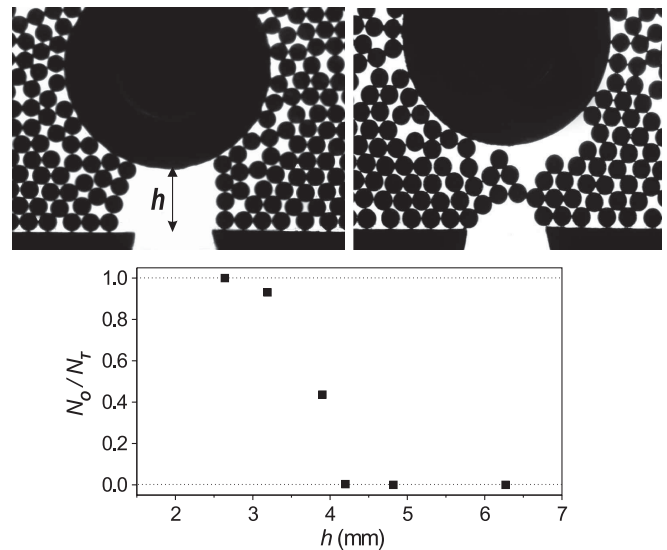


FIG. 2. Top: photographs of the two different kind of blocking arches found in this experiment: arches formed between the obstacle and the bottom (left) and arches formed just above the outlet (right). Bottom: ratio of the number of blocking arches formed between the obstacle and the bottom ( $N_0$ ) relative to the total number of arches ( $N_T$ ) registered for different obstacle positions.

average flow rate  $\langle q \rangle$  which is defined as the number of particles that pass through the outlet per second [Fig. 3(b)]. Clearly, the mean flow rate in a silo with obstacle is equal—or slightly higher—than in a silo without obstacle, unless the obstacle is too close to the outlet. For these values of  $h$  [represented by the shadowed region of Fig. 3(b)] the characteristic length which governs the flow is the distance between the obstacle and the bottom. The fact that the flow rate is rather homogeneous for  $h > 4$  mm suggests that  $\langle q \rangle$  is not related with the clogging probability reduction. Additionally, the slight increase of  $\langle q \rangle$  agrees with previous works performed in silos with outlet sizes large enough to avoid clogging [17,18].

The next variable we have considered is the packing fraction ( $\phi$ ) in the region of arch formation [22], just above the outlet as depicted in Fig. 3(a). Indeed, Roussel *et al.* have proposed that the probability of clogging in the filtration process is determined by the probability that a given number of particles coincide above a hole [23] which

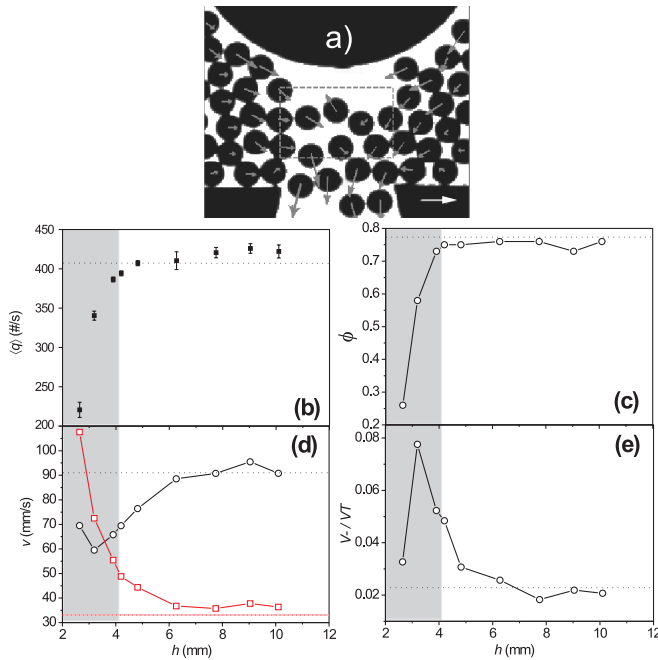


FIG. 3 (color online). (a) Photograph of the particles flowing out the silo with an insert placed at  $h = 4.20$  mm. The vector velocities are plotted with grey arrows. The arrow in the bottom of the silo is the scale and corresponds to 100 mm/sec. The dashed box indicates the region where the packing fraction and particle velocities are measured, which is 4.2 mm wide and goes from 1 mm to 2.5 mm height above the outlet [30]. (b) Average flow rate (in number of particles per second) versus  $h$ . The averages are calculated from 150 measurements of the flow rate in windows of 250 ms. The error bars indicate the standard deviation of these measurements. (c) Average packing fraction versus  $h$ . (d)  $\langle v_z \rangle$  ( $\circ$ ) and  $\langle |v_x| \rangle$  ( $\square$ ) as a function of  $h$ . (e) Number of negative vertical velocities with respect to the total number of registered velocities. Dashed lines indicate the values of all magnitudes when  $h \rightarrow \infty$ .

depends on the density of particles at this region of the space. In Fig. 3(c) we show that the average density above the orifice (measured in 12 different avalanches during 4 sec each) is practically constant for  $h > 4$  mm. Again, this result suggests that the packing fraction is not the variable behind the clogging reduction. The strong reduction of  $\phi$  for  $h < 4$  mm is, clearly, a consequence of the partial interruption of the flow in the lateral sides.

Finally, we measure the particle velocities above the outlet as it seems reasonable that the obstacle affects the velocity field in its proximities. High speed recordings have allowed the measurement of the particles velocities at very short time intervals (1/1500 sec) in the region depicted in Fig. 3(a). From these measurements, we can obtain (averaged during 48 sec over the whole measurement area) the vertical velocity  $\langle v_z \rangle$  and the absolute value of the horizontal velocity  $\langle |v_x| \rangle$  [24]. The results of  $\langle v_z \rangle$  and  $\langle |v_x| \rangle$  are displayed for different values of  $h$  in Fig. 3(d). Clearly, when the insert is approached to the orifice, the vertical velocity is reduced and the horizontal increased. In addition, for low positions of the insert we realized that the particles in the region of arch formation can displace upwards [see the higher particle in the region of measurement in Fig. 3(a)], a phenomenon which is less evident when the insert is at high positions [20]. Note that a similar effect has been observed when an intruder is displaced upwards within a static granular sample [25]. In Fig. 3(e) we present the number of negative velocities ( $V^-$ ) with respect to the total number of registered velocities ( $VT$ ) for different positions of the insert. Clearly, the number of negative velocities increases when the insert approaches the outlet which is a sign of the increase of upwards ejections. This unexpected effect could be related with the reduction of the clogging probability if it is thought that ejections result from groups of particles that collide above the outlet, but do not form an stable arch as they are not able to dissipate all their kinetic energy.

Based on existent results of panic flows through bottle-necks [2], we propose that the mechanism by which the insert prevents clogging is a reduction of the pressure exerted to the particles in the region of arch formation. This idea is supported by the reduction of the vertical velocity [Fig. 3(d)], and may be at the hearth of the increase of upwards movements of the particles [Fig. 3(e)]. As experimental measurements of the pressure within the granular bulk are difficult, we decided to perform an alternative numerical experiment in order to prove the effect of pressure reduction. This experiment consisted on measuring the clogging probability in silos filled with different layer heights, and hence, different pressures at the bottom.

We have used soft particle molecular dynamics simulations of disks (diameter  $d = 1$  mm) in two dimensions which have been proved to reproduce experimental results of the flow rate in a silo [26]. The simulated flat bottomed

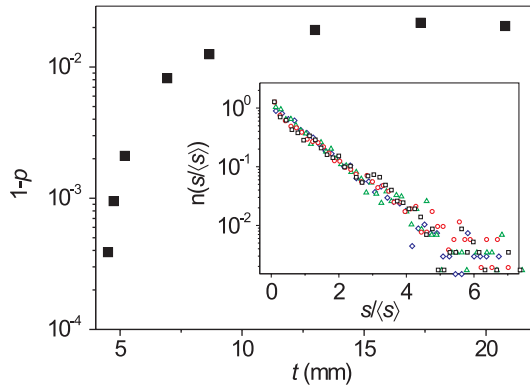


FIG. 4 (color online). Probability that a particle clogs the outlet ( $1 - p$ ) in a silo without obstacle filled with different layer thickness ( $t$ ). Inset: semilogarithmic plot of the avalanche size distributions rescaled by the mean avalanche size for  $t = 15$  mm ( $\diamond$ ),  $t = 10$  mm ( $\triangle$ ),  $t = 8$  mm ( $\circ$ ), and  $t = 5.5$  mm ( $\square$ ).

silo was  $15d$  wide and had an outlet size  $R = 3.5d$ . When particles passed through the outlet, they were placed with no kinetic energy on the top of the upper layer of grains, hence keeping the total number of particles constant. When an arch blocked the outlet, the number of particles fallen during the avalanche was registered and the flow resumed by removing three particles of the arch until 3000 avalanches were obtained. As mentioned above, different experiments were performed with different number of particles in the silo which are measured in terms of  $t$ , the layers thickness which one would get with an hexagonal packing.

The avalanche size distribution obtained in numerical simulations was found to be exponential independently on the layer thickness (Fig. 4). Hence the clogging probability ( $1 - p$ ) was calculated and the results reveal a strong dependence on the layer thickness: the thinner the layer the smaller  $1 - p$ . This result is in perfect agreement with the one presented in Fig. 1, with the layer thickness playing the role of the obstacle distance,  $h$ . Consequently, it seems clear that the pressure reduction by the insert is the physical parameter behind the decreasing of the clogging probability. A similar argument, based in a local pressure reduction, has been used in crowd dynamics to introduce a friction parameter which controls the human clogging [27]. Additionally, let us stress that our results also imply that the pressure reduction does not importantly affect the flow rate, as it has been shown in other experiments [28,29].

In this work, experimental results have been presented about the effect that an obstacle has in the granular flow through an orifice. We show that if the position of the obstacle is properly selected, a dramatic decrease of the clogging probability can be obtained. Although this phenomenon has only been studied for 2D silos, preliminary results in 3D suggest similar behavior [20]. Interestingly,

the clogging reduction effect is not caused by a net reduction of the flow rate, neither by a reduction of the density of particles at the very outlet. Instead, it is suggested that the insert induces a strong reduction of the pressure above the outlet. This behavior, which is proposed to be the one behind the clogging reduction, could have an analogy in the flow of crowds through bottlenecks, where it has been typically assumed that the main role of a column behind a door is to prevent straight motion of people towards the exit.

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