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Pipe Transport in Underground Mining: an Experimental Approach.

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Abstract. Transport of material through pipes or channels in mines or gravel quarries seems to be a simple and economic form of conveying blasted ore between different levels. Despite the apparent advantages of moving the material by means of the gravity force, there exists an important problem that makes the applicability of this method more difficult: the election of the pipe diameter to prevent clogging of the stones. It was R. Kvapil in the sixties who extended the ideas of granular flows in silos to underground mining. Nevertheless, after his pioneering works there are only a few manuscripts focused on this topic, and many questions remain unsolved. In this work, we present experimental results about the flow of particles (gravel) driven by gravity through tilted tubes. The amount of material discharged between clogs shows that the probability of clogging can be estimated by the same procedures introduced for silos. Finally, by changing the ratio between the tube diameter and the typical particle size, we discuss about the existence or not of a critical size beyond which clogging is not possible.

Keywords: blockage, avalanches, ore passes, domes
PACS: 45.70.Ht, 45.70.Mg

INTRODUCTION

Ore passes are vertical or inclined pipes dug out of rock mass. This kind of structures are commonly used in underground mining to transport the ore or waste from one level of the mine to another using the gravity driving force [1]. Unfortunately, this transport method may become problematic because of the formation of domes that block the flow of material [2]. These interruptions slow down the work progress in the mine and provoke extremely risky situations when they are removed. Indeed, the blockage of theses ducts is a critical point for the mine operation conditions and therefore their proper working is very important, not only for the safety conditions but also from an economical point of view.

It is commonly accepted that the blockage occurrence mainly depends on the ratio $\phi = D/d$, where D is the diameter of the chute and d the typical size of the particles. In literature, many works can be found about this topic but there is not any agreement about the value of ϕ that allows to assure the absence of clogging [3, 4, 5, 6]. Indeed, the figures range from 3 to 10, although the most accepted limit is $\phi > 5$ [5].

The problem of blockage has been widely investigated in the discharge of grains from silos and hoppers [7, 8]. In this geometry, the blockage phenomenon has been carefully analyzed from a probabilistic point of view, yet a debate still goes on about the existence of a critical size of the orifice above which clogging is not possible [9, 10, 11]. The experimental procedure in those works consists on measuring the avalanche size s, defined as the number of grains discharged between two successive clogs. A general finding is that, for a fixed ϕ, the distribution of avalanche sizes decays exponentially and can be characterized by only one parameter, i.e., the mean avalanche size $\langle s \rangle$. In order to explain this behavior, Zuriguel *et al.* proposed a simple probabilistic model. The authors suggest that the probability p that a particle passes through the orifice is constant during the whole avalanche. Hence, the distribution of avalanche sizes can be described by the following expression:

$$n_s = p^s(1-p) \tag{1}$$

where $(1-p)$ is the probability that a grain forms an arch that blocks the exit. The main consequence of this model is that there is a direct relationship between $\langle s \rangle$ and the clogging probability [11]. Therefore, the mean avalanche size, $\langle s \rangle$, was used to characterize the existence of a critical outlet size. Indeed, mean avalanche size tends to infinity when the ratio between the size of the outlet and the particle approaches a critical value ϕ_c of the outlet size. In other words, blockages are not possible for $\phi \geq \phi_c$. In the case of monosized spherical grains in a three dimensional flat bottomed silo, a value of $\phi_c = 4.94 \pm 0.03$ is reported which is very close to the one previously proposed by Kvapil [5]. In the same work [10], the authors also show that the shape of particles has an important effect on the value of ϕ_c.

Indeed, the importance of the presence of flat faces in the particles has been put on evidence in the last years. It has been qualitatively demonstrated that flat faceted par-

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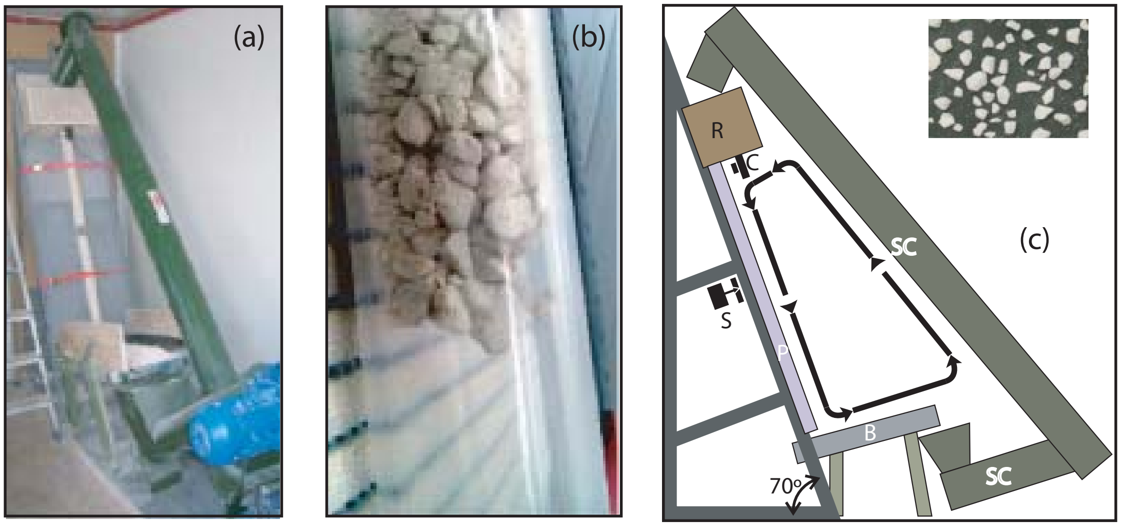

FIGURE 1. (a) Picture of the experimental setup where a blockage can be observed. (b) Zoom of a dome that blocks the flow of stones. (c) Sketch of the experimental setup where the arrow loop represents the movement of the material. B, conveyor belt; C, camera; P, pipe; R, reservoir of granular material; S, shaker; SC, screw conveyor. *Inset*: Detail of the limestones used in the experiment.

ticles oppose a significatively stronger resistance to flow out of a silo than rounded ones [12, 13]. Nevertheless, as far as we know, there is not any quantitative study of this problem in the literature.

In this work we present experimental results about the clogging of a poly-disperse, non-spherical and faceted granular material flowing along a pipe. Despite the absence of constriction (or bottleneck) - to which it has been traditionally attributed the responsibility of clogging- we find that the distribution of the avalanche sizes is exponential, in analogy to the silo case. Moreover, we show that the mean avalanche sizes for different ϕ can be fitted by the equation 3 and the value of ϕ_c is obtained.

EXPERIMENTAL SETUP

In Fig. 1 we show a picture of the experimental setup. It consists of a transparent polymethacrylate pipe fixed to a metal sheet tilted an angle $\theta = 70°$ from the horizontal. The length of the tube is 1.35 m and different diameters D ranging from 30 to 42 mm have been used for the different trials. The pipe is filled with a mixture of non-spherical limestone particles whose sizes range from 2 to 12 mm. The size of the stones is measured by image analysis and it is characterized by the equivalent circle diameter d defined as the diameter of a circle with the same projected area than the particle. The polydisperity of the sample quantified by this method is around 35%. We take as the characteristic sizes of the granulometry the values that correspond to the 50% and 95% of the cumulative distribution of the fragments ($d_{50\%}$ and $d_{95\%}$ respectively). Let us remark that assigning a circular shape to this material is a crude approximation; indeed, the material presents many flat faces (see inset of Fig. 1.c) which imply highly heterogeneous stress propagation [15]. As this issue is very complicated and involved, it will be studied elsewhere.

The granular material is feeded into the pipe from a reservoir at the top. At the bottom exit of the tube, the material is dragged by a conveyor belt that moves at a constant velocity (1 cm s^{-1}) and controls the discharge flow-rate (approximately 100 gs^{-1}). At the end of the belt, the material falls into a system of two screw conveyors that transport the particles again to the top reservoir. This refilling mechanism ensures that there are always particles in the top reservoir to fill the pipe.

The experimental protocol starts with the pipe completely filled with material. When the conveyor belt is switched on, the stones start to flow down the tube. A camera takes pictures every 0.5 seconds from a small region at the top of the pipe. Pairs of consecutive photographs are compared pixel by pixel. If there are no differences between two consecutive images, this means that the flow has been halted due to a blockage of particles down the pipe (Fig. 1). When such an event occurs, we wait for a few seconds to ensure that the clog is stable. Then, all the system is stopped and a computer records the duration of the avalanche t_{flow} defined as the time elapsed from the beginning of the flow until the blockage. Once the data are recorded, the flow is resumed by

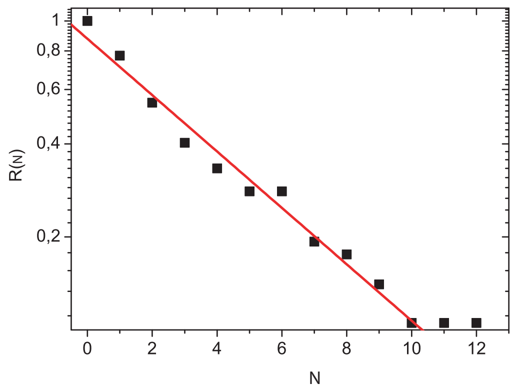

FIGURE 2. Survival distribution $R(s)$ of the avalanche sizes s, measured in number full discharged pipes. The squares are the experimental data and the solid line is a linear fit. Note the semilogarithmic scale.

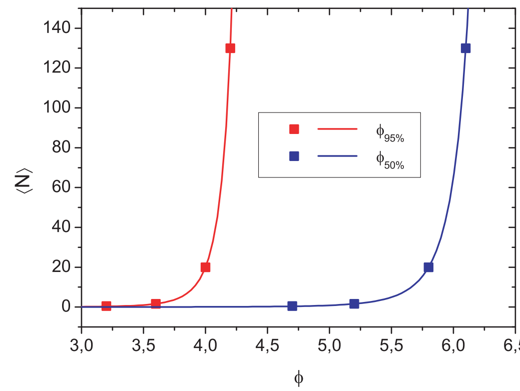

FIGURE 3. Mean avalanche size $\langle s \rangle$ in number of discharged tubes as a function of ϕ. Different symbols are used to indicate the characteristic size of the particle granulometry used to calculate the value of ϕ. The solid lines correspond to the fitting using equation 3.

breaking the blocking arch as a result of a vibration imposed to the whole pipe. This is accomplished with an electro-mechanical shaker placed behind the tilted metal sheet (see Fig. 1).

We also measure the mean time τ that it takes to discharge a full pipe filled of grains. Hence, we describe the avalanche size distribution by using the amount of material discharged between two clogging events, measured in number of discharged full pipes, $N = t_{flow}/\tau$. In the next section we will explain more in depth the reason for which we have decided to use this magnitude to measure the avalanche size.

RESULTS

We register around 200 avalanches for each different pipe diameter. From the data, we compute the survival function of the avalanche sizes $R(N)$ defined as:

$$R(N) = \int_N^\infty n(u)du = 1 - F(N) \qquad (2)$$

where $F(N)$ is the cumulative distribution function of the avalanche size distribution $n(u)$. From the data displayed in Fig. 2 (in semilogarithmic scale), it is clear that the survival function shows an exponential decay for a fixed value of D. As this feature is common for all the explored values of D, the results agree with an exponential distribution as introduced for the case of silos [8], embodied in Eq. 1. Hence, we can define p as the probability that a pipe as a whole will be discharged without forming a blocking arch.

At this point, the reason for measuring the avalanche size in number of discharged tubes can be explained. If this measurement had been done simply in number of particles as for the case of the silo, it becomes obvious that p will depend on the tube length. The longer the length, the higher the probability that a particle forms an arch at any position leading to a blockage. However, when measuring p in number of discharged tubes, it is expected that the results will not depend on the tube length if we assume that the clogging is equally likely at all the positions along the pipe. For instance, if we think of a tube which length is half the one used in this work, the probability that a particle gets clogged should be divided by two. But the number of particles in the tube is also divided by two, rendering the same probability of clogging per tube length that in the case under study. This issue can be also understood if we think of the time that one should wait until a clog is developed. If we divide by two the length of the tube, the probability of getting a clog in a given amount of time should be also divided by two. But the time that it takes to discharge this half-length pipe is also divided by two. Hence, we expect that the probability of getting a clog in the amount of time that the pipe needs to be discharged does not depend on the pipe length. Of course this idea needs to be checked and small effects could appear for very short pipes, where differences in pressure are expected and the clogging probability may not be uniform at every place along the pipe.

Once we have observed the exponential nature of the avalanche size distribution, we can use the mean avalanche size $\langle N \rangle$ as the characteristic parameter. With this parameter we study the dependence of the clogging on the size ratio $\phi = D/d$. Following the former analogy with the case of silos, the dependence of $\langle N \rangle$ on ϕ can be fitted by the expression [10]:

TABLE 1. Fitting parameters of the experimental data using Eq. 3.

	$\phi_{50\%}$	$\phi_{95\%}$
A	27 ± 5	3 ± 1
γ	5.6 ± 0.4	5.5 ± 0.8
ϕ_c	6.8 ± 0.1	4.7 ± 0.1

$$\langle N\rangle = \frac{A}{(\phi_c-\phi)^{\gamma}} \tag{3}$$

where A, γ and ϕ_c are fitting parameters. This expression assumes the existence of a critical radius ϕ_c beyond which the clogging probability becomes negligible. In Fig. 3, we display the experimental data of $\langle N\rangle$ versus ϕ. The two different sets of data correspond to the two different values of ϕ obtained for each one of the characteristic particle sizes used ($d_{50\%}$ and $d_{95\%}$). In both cases the experimental data are well fitted by equation 3. The values of the fitting parameters are summarized in table 1.

We can see that the values of ϕ_c are consistent with those reported in the literature [3, 4, 5, 6]. Indeed, the value obtained for $\phi_{95\%}$ is very close to the recommendations of Kvapil [5]. In the case of $\phi_{50\%}$, the value of ϕ_c is larger as the characteristic size of the particles is smaller. The values obtained for ϕ_c are only a first approximation because the fitting parameters can be very sensitive to the measured range of ϕ. Then, a better estimation of ϕ_c can be obtained if larger values of ϕ are measured.

CONCLUSIONS

In this work we have studied the blockage probability during the flow of a granular material along a pipe. Due to the resemblance to the silo clogging problem, we have addressed the study with a similar procedure. The results show that the exponential distribution of the avalanche sizes is also present in this geometry. Then, the probability of clogging can be characterized by the mean avalanche size and a critical value of the ratio between the pipe diameter and the particles can be estimated. The value obtained for this critical size is close to the one obtained for spherical grains in a flat bottomed silo, but this could be a mere coincidence. Indeed, one may expect that clogging in a vertical pipe is more difficult than in a bottleneck. But at the same time, it seems clear that faceted particles as the ones used here should lead to clogging more easily than spherical ones.

In any case the results reported in this manuscript reveal that arching in granular materials can be analyzed by similar methods regardless of the system geometry. For this reason, the analysis of flow rate intermittencies -which have been reported to be strongly related to clogging in silos [14]- seems the natural step forward. Finally, from a practical point of view, the results obtained here are the first important attempt to predict safety working conditions for the the diameter of ore passes in mining guaranteeing complete absence of clogging events.

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