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RESEARCH REGARDING THE GRAIN DISCHARGE SYSTEMS DESIGN

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Abstract: The scientific paper presents the properties of dry granular flows and the recent advances made by scientists in understanding their rheological behavior. The shear rheology at the steady state of granular materials is investigated quasi–statically and inertially. The difference between the low–density collision flux and the dense friction flux is clarified. Finally, the constant granular flow on a slope and its instability in low density regime are investigated and an attempt is made to find suitable design solutions to solve the problems in the flow process. The optimal parameter in which the constant collision flow is achieved is determined, when changing the angle of inclination and the density of particles (cereals).

Keywords: grains, discharge sytems, bunkers, flow patterns

INTRODUCTION

Many traditional methods, processes and tools used in grain storage are constantly being replaced by automated systems and equipment due to technological advances. Rules and regulations by government agencies based on current health and environmental concerns restrict the use of chemicals and insecticides in grain storage. Also, in order to respect the quality assurance aspects, the continuous supply of cereals as food for human society and to meet the growing global standards, it is imperative that the agricultural industry adopt new quality management systems to reduce losses and maintain quality and safety during grain storage. (Neethirajan, S., 2007)

Bunkers are often used for long–term grain storage, with minimal loss of quality and quantity of stored products. Ideal for storing various cereals, seeds and granular materials, taking into account the fact that the products are prone to fermentation, they require special attention to maintaining quality. For this, it is necessary to design and build special technological equipment. (Mircea C., Nenciu F., 2020)

For a long time, designers of silos and bunkers have been trying to complete research work to codify the rules of eccentric filling and unloading. Some experiments and investigations on silo wall pressures have been intensively studied by scientists (Borcz A., 1991; Jenike A.W., 1964) Blight G.E., (1991) has discovered that near the outlet, the Jenike theory of pressures is also valid in the case of eccentric emptying.. Ayuga F. și colab. (2001) investigated pressure distribution in the process of unloading bulk granular products in a silo with central and eccentric holes. Molenda M. și colab. (2002) investigated the loads of bunkers induced by eccentric filling and seed unloading. It was found that the eccentric discharge induced much higher dynamic moments than the static moments on the hopper wall.

Numerous attempts have been made to investigate eccentric filling and unloading in bunkers, trying to indicate the main additional problems that occur during eccentric unloading, ie asymmetric loading of the hopper wall which can lead to quite different design of the structure from what was known. until the present. These additional, unexpected problems that occur during eccentric filling and unloading are considered to be a major cause of hopper failures. (Sielamowicz I., 2004)

Nenciu F. (2021) and Mircea C. (2020) emphasized the importance of proper designing of bunkers in wheat processing facilities, especially when performing seed conditioning. The technologies used in industry have to be updated accordingly to the new technological advances regarding the use of sensors (Nenciu F., 2014), and must take into account the optimized technological flows, in accordance with the expected quality of the products, the time required for processing or the characteristics of the materials that are being processed (Mircea C, 2020).

MATERIALS AND METHODS

This paper presents the theory of bulk grain flow through a logical, theoretical approach to understanding and managing this concept. Jenike Andrew developed test methods, equipment and design techniques and performed experiments to confirm and refine innovative analysis. (Jenike A.W., 1964; Mehos, G., 2016)

Prior to Jenike's research, silos and bunkers were usually designed primarily primarily architecturally or from a manufacturing point of view (e.g., hopper walls were tilted 30 degrees vertically to reduce material waste or 45 degrees to minimize margin requirements to simplify design calculations). However, extensive experience has shown that designing equipment without regard to the actual bulk materials that are handled often leads to flow problems such as arching, ratholing, irregular flow and even lack of flow. By measuring the flow properties of a solid bulk material, the flow behavior can be predicted so that the design of the bunkers is more reliable. (Golshan S., 2019).

Two main types of flow can occur in a hopper or in a silo: mass flow and funnel flow (Figure 1). In the mass flow, the entire bed of cereal seeds is in motion when the material is discharged through the outlet. This behavior eliminates the formation of stagnant regions in the vessel and provides a constant and continuous flow sequence that provides a more uniform speed profile during operation. A uniform speed profile also helps reduce the effects of segregation. (Liu W., 2019)

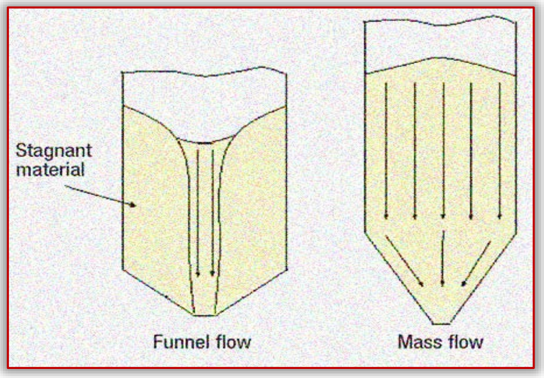

Figure 1 – Two types of flow patterns can occur when a bulk solid is discharged from a bunker, hopper, bin or silo: A typical funnel flow pattern is shown on the left, and a mass flow pattern is shown on the right (Jenike A.W., 1964)

On the other hand, in the flow of the funnel, an active flow channel is formed above the outlet, but the granular material remains stagnant (called ratholes) at the periphery of the vessel. The funnel flow can cause irregular flow, exacerbate segregation, reduce equipment processing capacity, allow particle degradation (leading to agglomeration and damage) in stagnant regions. Depending on the size of the equipment, the flow of the funnel can also induce heavy loads on its structure, due to the agglomeration of the material and the eccentric flow is formed inside the channel. (Rogovskii I., 2019)

For many powdery and granular materials, flow problems can be eliminated by ensuring a mass flow pattern in the vessel. The first step in achieving mass flow is for the designer to ensure that the converging walls are steep enough and have sufficiently little friction to allow the bulk materials to slide along them. This is done by first testing the material to measure the friction of the wall and then calculating the minimum angle of the hopper that will allow mass flow. (Al–Hashemi, H.M.B, 2018).

— Optimal angle for the mass flow

Once the results of the wall friction are known, the recommended angle for the hopper to ensure the optimal mass flow can be easily calculated. The wall friction angle (φ’) is obtained following the method described in ASTM D–6128 (ASTM–6128, 2006). The test is performed using a tool (shown in Figure 2) that involves placing a sample of powder inside a retaining ring on a flat coupon of wall material. Various normal loads are then applied to the powder, and the powdery material inside the ring is forced to slide along the stationary wall. The resulting shear stress is measured as a function of the normal stress applied.

After a series of values have been recorded, the wall efficiency is identified by plotting the shear stress against the normal stress (Figure 3). The wall friction angle (φ ') is the angle that is formed when a line is drawn from the origin of that graph to a point on the wall.

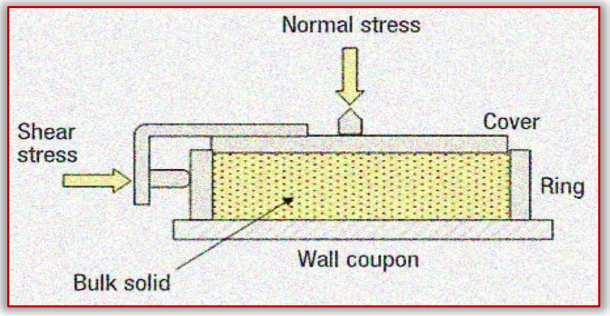

Figure 2 – By measuring the force required to slide a sample of powder along a wall coupon, the angle of wall friction can be determined (Mehos G., 2016)

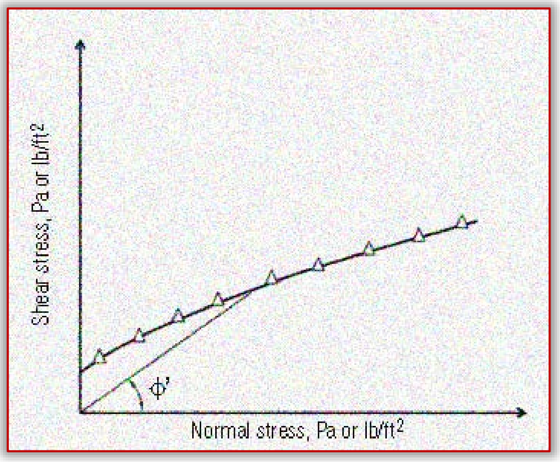

Figure 3 – The angle of wall friction (φ’) is determined by drawing a line between the wall yield locus (which is constructed by plotting shear stress against normal stress), and the origin, as shown here Δ, φ. (Mehos G., 2016)

Jenike found that the angle of the hopper needed to allow it to flow along the walls depended on the friction between the pubes and the walls, the friction between the powder particles and the geometry of the hopper. The design diagrams originally developed by Jenike provide permitted hopper angles for mass flow, given the values of the wall friction angle and the actual internal friction angle (which is determined by the shear cell testing) (Schulze D., (2007; Cui X, 2013; Armanini A., 2013).

The diagrams below are summarized in Figures 4 and 5 for conical and plane bunkers (eg wedge–shaped bunkers and transition bunkers, respectively). It is recommended that the outlet of a wedge–shaped hopper be at least three times its length to apply the relationship in Figure 5. (Jenike A.W., 1964)

The permissible values of the hopper angle θ '(measured vertically) are on the x–axis, and the values of the wall friction angle φ' are on the y–axis. Any combination of φ ’and θ’ that falls within the limiting mass flow region of the diagram will ensure the mass flow.

Bunkers with circular or square holes must not be designed at the theoretical value of the hopper angle. Otherwise, a small change in the properties of the powder can cause the flow pattern inside the hopper to change from the ground flow to the funnel flow, accentuating the risk associated with flow problems. A safety margin of 3 degrees is recommended (relative to the angle of the mass flow hopper given in Figure 4).

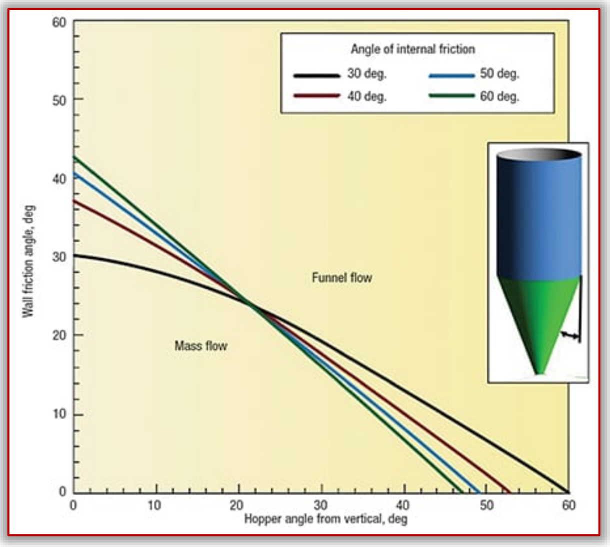

Figure 4 –Theoretical diagrama of mass–flow bunker angles for bunkers with round or square outlets. (Mehos G., 2016)

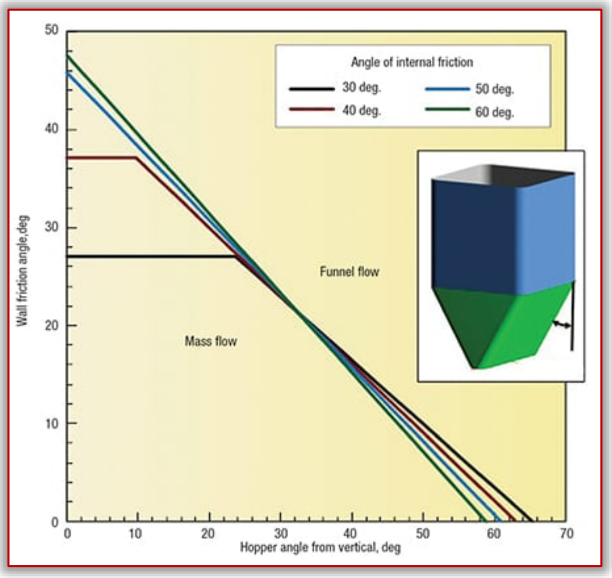

Figure 5 – This plot shows the recommended wall angles to ensure mass flow in a hopper with flat walls and a slotted outlet (Mehos G., 2016)

— Minimum outlet size

The opening of the hopper section must be large enough to prevent the development of cohesive springs or stable flows. The required size of the outlet depends on the cohesive strength and bulk density of the solid material. Cohesion strength is measured by shear cell testing, as described in ASTM D–1628 and D–6773 (ASTM D–6773, 2008). Figure 6 shows schematic diagrams for two common cell shear tests. A powder sample is placed in a cell and then pre–sheared – that is, the sample is strengthened by exerting a normal load and then sheared until the measured shear stress is stable. This is shown in Figure 7, by point (σss, τss).

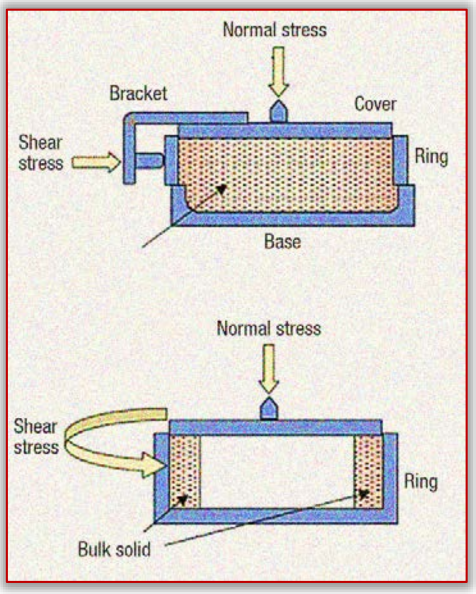

Figure 6 – Two versions of the shear cell tester — the direct shear cell tester (top) and the ring shear cell tester (bottom) — are used to measure the cohesive strength of bulk solids (Mehos G., 2016)

Then the shearing step is performed. During this stage, the vertical compaction load is replaced with a smaller load, and the sample is sheared again until it fails. These pre–shear and shear steps are repeated at the same level of consolidation for a series of reduced normal stresses, and the yield of the hopper angle is determined by plotting the shear stress against the normal stress (Figure 7).

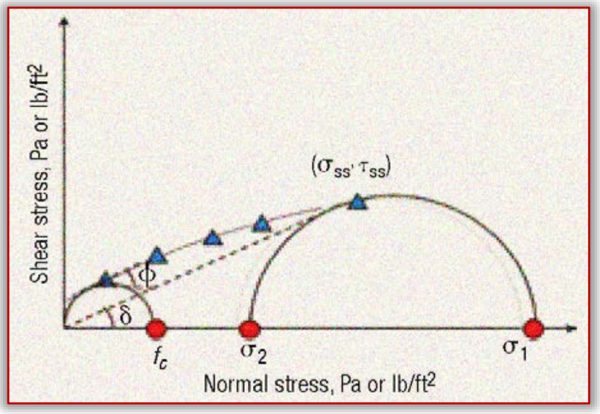

Figure 7 – A Mohr's circle drawn through the steady–state point and tangent to the yield locus gives the major consolidation stress. A Mohr's circle tangent to the yield locus that passes through the origin gives the cohesive strength. (Mehos G., 2016)

RESULTS

Cereal seeds interact, both by friction and by collision through a contact surface. From a phenomenological point of view, the material flows like a liquid with special features. To better understand this regime, different flow configurations were investigated, the most common being shown in Figure 8. These can be divided into two families: limited flows between walls as in shear cells and flows flowing on a free surface. with an inclined plane. (Forterre Y., 2009). Their characteristics in terms of speed profiles, density profiles, speed fluctuations are discussed in detail in this paper.

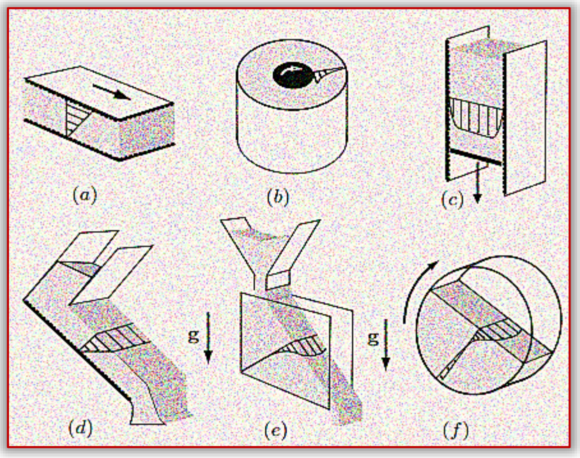

Figure 8 – Different configurations used to study granular flows. (a) Plane shear (b) Couette cell (c) vertical silo (d) Inclined plane (e) Heap flow (f) rotating drum (Forterre Y., 2009)

Dense granular flows belong to the family of visco–plastic materials, due to the two broad properties. First, there is a flow threshold, although it is expressed in friction instead of a flow voltage, as in a classic visco–plastic material. Second, when the material flows, the dependence on the shear rate is observed, which gives a behavior similar to the liquid, namely viscous. The next section presents recent advances in understanding the rheology of dense granular flows. We first present the flat shear configuration, which provides the basic ideas that allow the proposal of a constitutive law for dense granular flows. The application to other configurations is discussed and the limits of this simple local rheology are discussed. (Rogovskii I.L., 2020)

For example, it is considered a granular material consisting of particles with diameter d and density ρp under a closing pressure P. The material is bounded between two rough plates by a pressure P imposed on the upper plate.

The material is sheared at a given shear rate $\gamma = V_w / L$ imposed by the relative displacement of the upper plate at a speed V_w. (Figure 9). In the absence of gravity, the balance of force implies that both the shear stress $\tau = \sigma_{xz}$ and the normal stress $P = \sigma_{zz}$ are homogeneous throughout the cell. This configuration is simpler to study the rheology of granular flows, namely to study how the shear stress τ and the volume fraction φ vary with the shear rate γ and the pressure P.

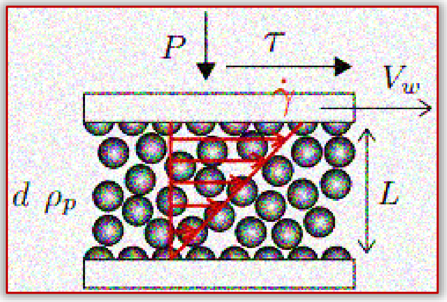

Figure 9 – Plane shear at constant pressure (Pouliquen O., 1999)

An important observation made by Da cruz F., et al. (2005) and Lois G., et al., (2005) is that in the simple shear configuration for infinitely rigid particles, dimensional analysis strongly constrains the stress / shear relationships (Midi G.D.R, 2004). For large systems (L / d >> 1) the rigid particles are controlled by a single dimensionless parameter called the inertial number:

$$I = \frac{\gamma d}{\sqrt{P/\rho_p}} \qquad (1)$$

Consequently, dimensional analysis requires that the volume fraction φ is only a function of I and that the shear stress τ must be proportional to the normal stress P, which is the only stress scale of the problem. The constitutive laws can then be written as follows:

$$\tau = P\,\mu(I) \text{ and } \varphi = \varphi(I) \qquad (2)$$

where: μ (I) is a coefficient of friction, which depends on the inertial number. The shape of the coefficient of friction μ (I) and the volume fraction φ (I) are provided by numerical simulations using discrete element models and by experimental measurements.where μ (I) is a coefficient of friction, which depends on the inertial number. The shape of the coefficient of friction μ (I) and the volume fraction φ (I) are provided by numerical simulations using discrete element models and by experimental measurements.

Figure 10 shows a summary of the results from various studies for 2D (disks) or 3D (spheres) systems. It is observed that the coefficient of friction μ is an increasing function of the inertial number. Friction increases when shear rate increases and / or pressure decreases.

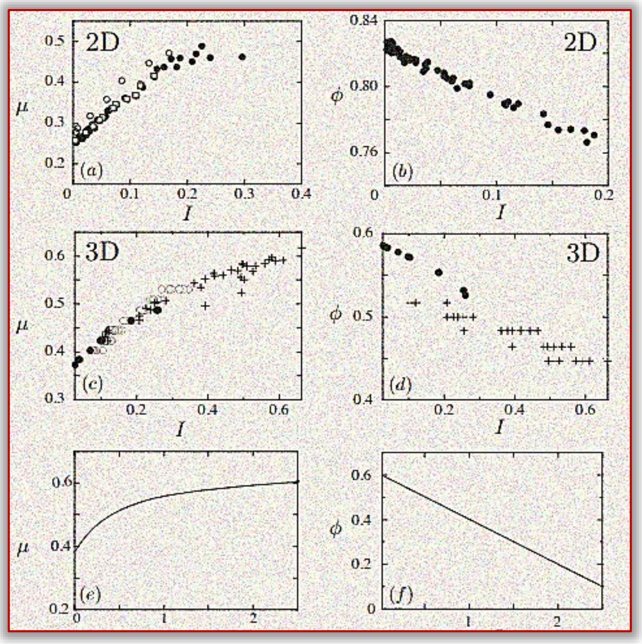

Figure 10 – Friction law μ(I) and volume fraction law (φ(I)); (a) (b) for 2D configurations with disks (c) (d) for 3D configurations with spheres; (e) (f) empirical analytical law proposed (eqs. (3) data form (Silbert, L.E., 2003)

Within the quasi–static flows (I–> 0) the coefficient of friction tends towards a constant. The volume fraction also varies with I. It starts from a maximum value when (I–> 0) and decreases more or less linearly with I. It is interesting to note that in the range of the inertial number corresponding to the dense flow regime, the macroscopic friction coefficient μ (I) and the volume fraction φ (I) do not depend on the microscopic properties of the grains. Changing the grain return coefficient or changing the coefficient of friction between the particles (as long as it is not zero) does not change the macroscopic friction. (Singh, A., 2015)

The inertial number consists of important parameters that control the rheology of dense granular regimes. It can be interpreted in terms of the ratio between two time scales: a microscopic time scale $d/\sqrt{P/\rho_p}$, which represents the time required for a particle to flow through an outlet hole of size d under pressure P and which gives the typical time interval of rearrangements; and a 1 / γ macroscopic time scale related to the mean deformation.

This interpretation allows a more precise classification of the different flow regimes. The value of I corresponds to a quasi–static regime in the sense that the macroscopic deformation is slow compared to the microscopic rearrangements, while the high values of (I) correspond to the fast flows. Dimensional analysis emphasizes that in order to move from the quasi–static regime to the inertial regime, it is due either to the increase of the shear rate or to the decrease of the pressure. This inertial number is also equivalent to the square root of the Savage number or the Coulomb number introduced by some authors as the ratio of collisional stress to total stress. (Ancey C, 1999; Savage S.B., 1984).

CONCLUSIONS

It was found that several factors affect the angle of rest, such as the static slip coefficient of friction, the rolling friction coefficient, the return coefficient, the size and shape of the particles, the amount of material used in the measurement and the method of measurement. The reported data indicate that the resting angle increases with the roughness of the particles and the affected surface, the slip and friction coefficients, the moisture content, the deviation from roundness and the increase in the speed of the rotating drum. In contrast, the angle of rest decreases with the amount of material used in the measurement, the particle size and the lifting speed of the hollow cylinder growth.

The rest angle is not always equal to the tip or the residual internal friction angle. In direct shear tests, the factors that ensure that the rest angle is equal to the residual internal friction angle are the method of sample preparation and the sample conditions, such as moisture content, maximum dry density, particle size, etc. Therefore, the resting angle should be considered as an estimate of the residual internal friction angle only in certain circumstances. Although the measurement of the angle of rest is quite simple, slight differences in the conditions of the sample or the method of measurement will lead to erroneous results.

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