A Critical Review on Modeling and Analysis of Granular Matter Flows

MELDA OZDINC CARPINLIOGLU
Mechanical Engineering Department
Universityof Gaziantep
Gaziantep 27310
TURKEY
melda@gantep.edu.tr http://www.gantep.edu.tr

Abstract: - A comment on the modeling and analysis of granular matter flows is presented in this paper. The relevant literature concerning the flow pattern determination particularly in loading/ unloading (storing, mixing, feeding)processes of bulk solids in a variety industrial applications is referred with a historical treatment. A criticism on the state of art is provided in terms of available terminology , basic equations and methodology *to determine the unknowns and/or discrepancies which need further research.*[1]A devised experimental study to determine the influence of particle shapes of non-spherical / irregular fibrous platelets and porosity of the medium as a special granular matter flow through a gravity-driven silo discharge is outlined .

[1]*In the text , the primary points to be taken into consideration are given in Italics to increase the readability.*

Key-Words: - Granular Matter Flow, Beverloo's Equation, Gravity Discharge

1 Introduction

A granular solid is usually described as "a collection of discrete solid particles " and the concept of "granular solid flow "is as old as human being .The modeling and analysis of granular flow is critically important for the efficiency and optimization of industrial processes in a great variety of applications of agriculture ,food, pharmaceutical and chemical fields of engineering. The primary application cases of storing ,mixing and feeding of granular matter can be treated as the different realms of flow. Since the flowing medium-fluid has its own nature, modeling should be initiated with the specification on " fluid" . Campbell [1] in his extensive review utilized basic internal force transmission and contact mechanics by disregarding the cohesion between the particles. He classified flow regimes as quasi-static-slow and rapid ones paying attention to the elastic perspective of the field. He concluded that granular flow varies under the conditions of controlled stress and concentration. Slow flow is called also as Coulomb flow overwhelming interaction between the particles while in rapid granular flow particles cascade over each other interacting only by short collisions . However division is rather arbitrary since both can occur simultaneously.([2] Zhou and Sun,2013) Meanwhile as Savage [3] (1984) indicated that flow was also a function of the distribution of the granular matter since he noted that in dense granular flows two extreme regimes of inertial flows , quasi-static shearing flows and transitional flows existed . *It is known that transitional flows are not well understood* . Zhou and Sun [2] concluded that *development of granular flows from initially deposited state* *to a fully developed flow is not well investigated* . In the classification of granular flows a variety of industrial applications was considered. They used dry granular flows along sloping channels using a particle flow code in 3-D. They introduced a new criterion combining Savage Number, Sa and granular temperature T. They used flow velocity profiles, channel confinement effect, shear rate inside the granular body, variation in flow regimes by Savage Number and degree of fluctuation through T .

Meanwhile Wildman and Huntley(2008) [4] considered 3-D dry granular flows and validated kinetic theory based models of rapid granular flows using experimental techniques of positron emission particle tracking and magnetic resonance imaging. They considered that when a granular system flows the particles undergo fluctuations in position and velocity superposed upon the mean motion of the flow. They preferred stresses and heat transferred due to fluctuations .*Anisotropy and polydispersity can be further considered in granular flow modeling through kinetic theory models.*

The simulation of a variety of granular flows using discrete element method have been studied by many researchers. The major fields of study are given as physical modeling improvements and simulation of large scale geometrically complex systems (Cleary and Sawley;2002) [5] DEM simulations particularly 2-D ones used either mono-disperse or slightly poly-disperse systems. *However most of the neglected aspects in DEM studies is on the effect of particle shape and inter-particle cohesion. These both contribute to shear strength of granular assembly and determine where the material will fail and flow and when it will remain stationary.* For realistic hopper flow effect of particle shape on flow behavior and change in flow pattern discharge flow rate ,discharge velocity and wall forces with blockiness and aspect ratio of the particles are described. Also DEM models qualitatively predict mass flow with some accurate predictions of funnel flow and phenomena such as rat-holing are yet to be obtained.

In reference to discharge from a silo most common devices of chutes and hoppers are gravity driven devices. Therefore flowability of matter is critically important .*Discharge of particles from hopper generates flow and this flow resembles laminar flow of viscous fluids . Free flowing is the basic requirement however this depends on particle characteristics . Cohesive or poorly flowing powders with unpredictable behavior is a problem as simply.*(Vlachos Chang,2011) [6]

Analytical prediction of gravity discharge rate of granules from small orifices requires an explicit functional form incorporating the effects of i) size and shape of orifice ii) size distribution and shape of particles iii) inclination of hopper walls .The poly-disperse spherical and non-spherical particles in mixtures of binary or ternary having fine 100 micron less and coarse greater than 100 micron sizes needs further investigation. In fact discharge flow pattern affects the temporal evaluation of silo content during discharge. In silos main discharge patterns are :i) mass flow in which all silo content in motion ii) funnel flow with little re-mixing of the silo content (Engblom et al,2012)[7]

Oldal et al (2012)[8] demonstrated that constant discharge rate is caused by the formation and collapse of arches in bins . They developed a new equation for the discharge rate determination as a new alternative for Beverloo's [9]and Johanson[10] approaches . The major difference is not on the predicted discharge rate but proper description of the physical process. They determined the cross-sectional velocity distribution at the outlet also.

The recent experimental study of Mellmann et al (2014) [11] is the only one which concentrates on the influence of particle form in flowability. *In a free flow case they found that shape of the particles caused variation in matter flowability and was more dominant than size of the particles* . They also introduced dimensionless coefficient Froude Number ,Fr of discharging flow from a level model silo with a wedge shaped hopper as a function of flowability. They noted that Froude number decreases with an increase in particle elongation value increases in line with the reduction in flowability.

Since most of the experimental studies were directed to determine the influence of a specified parameter/s on the flow of a specific matter flow for the practical necessities a need for an overall perspective is essential. Our primary emphasis herein is devoted to the present state of art regarding modeling of discharge –feeding and mixing of granular matter with the determination of unknown points and conflictions through tabulated information. Although the application of positive and negative pressure gradients is possible for both the loading and unloading of granular solid matter *,gravity driven free flow of granular matter is only considered due to its severe dependence on the particle and medium storage characteristics and thereby the difficulty of flow controlling*.

2 The Analysis through Free flow of Granular Matter Discharge Equations

Unloading of a granulate matter in a discharge process is directly related to the storage facility and the nature of medium. The size distribution and pattern is at primary importance for a gravity driven flow. The analysis of unloading is usually directed to determine the problems denoted as segregation ,presence of dead zones, jamming, and interlocking mainly. However the mechanisms causing any of the problems are not known totally as can be denoted by McCarthy (2009)[12] segregation may be caused by 13 different mechanisms . Meanwhile Tang and Pury (2004)[13] outlined the mechanisms as : trajectory, sieving, fluidization, agglomeration. *It is known that particle size difference is the main factor leading segregation . Remy et al (2011[14]) concluded that poly- dispersity effects must be studied. The larger the particle size difference the larger the possibility of segregation. Tailoring the width of size distribution is said to be critical. However the influence of particle shape is not known clearly.*

A robust empirical equation is given for discharge from an orifice which is described by Beverloo's Equation as follows:

$$W= C \rho_b g^{0.5}(d-kd_p)^{2.5} \quad (1)$$

where W is discharge rate ,ρ_b is bulk materials density d is orifice –outlet size and d_p is the particle size k is a constant evaluated between 1.5-3 C is varying between 0.55-0.65. The equation was tested for mono-sized particles where $d_p<d$. *However the constant discharge rate –physical process is not understandable through it*.

Oldal et al [8] in their recent study proposed the following equation

$$W= \pi/6 \ (\delta 2g)^{0.5}\rho (d-d_p)^{2.5} \quad (2)$$

where δ is shape parameter defined as h/d for a variety of arches artificially formed and h is the height of the arch. *Their proposal is on the modeling of outflow as the formation and collapse of arches in silo during the discharge process similar to sand clock process. They used the range of shape parameter $0.3< \delta < 0.46$. The defined validity range of d is between d_p and 0.6 D. However there is no information about the influence of form of the particles on discharge rate determination. There is also no satisfactory explanation on the influence of a variety of different shape binary mixtures.*

2.1 Description of Future Research Topics

As an overall treatment industrial granular flow applications with common problems can be categorized as follows:

i) Storing of large granular materials in large containers –called silos (Design of silo and problems of storage-mixing)

ii) Discharge and mixing of granular materials from containers (A variety of outflow cases and related problems as arching segregation e.t.c)
iii) Transportation of granular materials through long distances (Flow modes as dense and dilute phase ones governed by the characteristics of transporting fluid flow)

Among these listed applications the first two have a different feature from the third one. The modeling of industrial granular particle flow by itself can be understood in the first two cases. The particular attention is devoted to them in this presentation. The modeling of granular materials can be solid or liquids . The basic material properties of the granular assemblies can be listed as follows:

i) Physical and chemical material characteristics (Physical and chemical composition , size and shape of the parameters, material density)
ii) Characteristics of granular assembly as a bulk medium -Size distribution of the granular assembly (mono-sized and poly-sized patterns, bulk density ,voidage porosity) likewise the sample reference of Saad etal(2011)[15]
iii) Discharge-outlet characteristics (Operation concept as a gravity driven flow or a forced operation handled by either blowing or suction ,Outlet characteristics size shape and pattern)

In the available literature most of the experimental studies concerned the influence of discharge characteristics using a variety of orifices and even using gravity and forced flows . However in order to understand more , the unknown points should be clearly defined . The following list is for the purpose:

1) The modeling of granulate matter flow in discharge and filling loading and unloading from a large tank should have similar behavior. The particle characteristics are the dominant parameters.
2) There is almost no consensus on the flow rate determination therefore control of granulated matter flow from storage vessels .
3) The flow models are slow and rapid types but no clear identification method. Particle size differences are either reason of flow mixing or bridging segregation . No identification is on particle shape differences in matter composition. Binary mixtures of different shape and different size should be looked at.
4) The gravity flows and forced flows have similar gaps but treatment of modeling flow as a fluid for each case should be investigated.
5) The need for dimensionless parameters to differentiate flow modes is apparent.

3 Conclusion

The experimental case under consideration [16] is discharge of granular matter from a cylindrical silo by means of a flat bottom and wedge shaped hopper . The discharge is a gravity driven one to determine the influence of granular matter characteristics. The granular matter is of non-cohesive nature and has a variety of forms ranging from fibrous platelets to spherical particles. The basic investigation topics of the research can be given as follows:

1) The distinction between the slow/rapid flow modes
2) Development of flow from a deposited case which is under the conditions of stress and consolidation
3) The influence of mono and poly-dispersed configuration of the medium ,and the storage pattern in silo
4) The influence of particle shape on flow
5) Applicability of Beverloo's Equation for poly-dispersed , non- spherical particle shape of granular matter with a variety of silo storage patterns

The need for common non-dimensional parameters describing a variety of granular matter flow –modeling the particle ,the medium and flow is filled by the investigation. In this respect the content discharge rate calculation through an orifice located at flat bottom and in a wedge shaped hopper as a function of a variety of non-spherical particles and fibrous particles -platelets in reference to a common comparison parameter of sphericity and particle characteristic size is considered. The influence of binary mixtures –poly dispersed granular matter in unloading is considered paying attention to the generation of controlled flow and to overcome the problems of bridging, arch formation and particularly interlocking . The silo-storage pattern is considered. The experimental investigation consisted of discharge of modeled silo content as separate test systems. In the first system a single granular matter stored in random loose distribution was used. In the second system a storage of two –three different granular matter distributed as layer by layer vertical alignment and center – side horizontal alignment was used. The granular matter discharge was through a variety of orifices having different outlet diameters, D located at the center of flat bottom and conical bottom plates to determine the influence of shape and size of orifice outlet. The granular matter was a variety of bulk particles having different physical characteristics. The modeling of the particles, measurement of the physical characteristics of particles and their storage characteristics were covered before the discharge measurements. The particles of granular matter were lentil, mung bean, semolina, zeolite, polyethylene pellet, empty capsule, and filled capsule. The shapes of the particles ranged from regular spherical to non-spherical irregular ones. The utilized particle characteristics were defined as the size which was given by equivalent particle diameter d_{eq} , shape of the particle which was defined by sphericity Φ. The silo storage was described by content bulk density ρ_b and porosity ε. The covered ranges were $0.8mm < d_{eq} < 12.6mm$, $0.01 < d_{eq}/D < 0.315$, $69 kg/m^3 < \rho_b < 881 \ kg/m^3$, $0.01 < \varepsilon < 0.91$, $0.027 < \Phi < 1$,. The bulk density ρ_b, equivalent diameter d_{eq}, sphericity Φ for the poly size – poly dispersed modeled cases were determined using the introduced modeling equations.

As an overall perspective of the conducted study a published result on the proposed modified Beverloo's Equation as a function of silo storage pattern is given in Figure 1 [17] .

The proposed modified Beverloo's equation is given as

$$W= 0.56 \rho_b \sqrt{g} (D - 1.5d_{eq})^{2.5} \qquad (3)$$

The experimental data belonging to mono-sized single granular matter are in good conformity with Eq'n 3. The experimental data gathered from discharge of layer-layer silo pattern can also be fitted with Eq'n 3 . In spite of the greatest departure observed with side-center pattern of some cases , proposed equation with the utilization of d_{eq} for non-spherical particles is suitable for a variety of silo storage patterns.

Ackowledgements

The financial support of BAP –University of Gaziantep is greatfully acknowledged

References:

[1]C.S.Campbell, "Granular material flows-An overview ",Journal of Powder Technology, 162(2006) 208-229

[2] G.G.D Zhou, Q.C.Sun" 3-D numerical study on flow regimes of dry granular flows by DEM" Journal of Powder Technology 239(2013) 115-127

[3] S.B Savage " The mechanics of rapid granular flows " Advances in Applied Mechanics 24(1984) 289-366

[4] R.D Wildman J.M.Huntley "Experimental measurements and modeling of rapid granular flows" Journal of Powder Technology, 182(2008) 182-191

[5] P.W.Cleary, M.L.Sawley "DEM modeling of industrial granular flows: 3-D case studies and the effect of particle shape on hopper discharge Applied Mathematical Modelling 26(2002) 89-111

[6] N.Vlachos I.T.H. Chang " Investigation of flow properties of metal powders from narrow particle size distribution to polydisperse mixtures through an improved Hall-flowmeterJournal of Powder Technology, 205(2011) 71-80

[7]N.Engblom, H.Saxen, R.Zevenhoven,H.Nylander,G.G.Enstad " Effects of process parameters and hopper angle on segregation of cohesive ternary powder mixtures in a small cylindrical silo" Journal of Advanced Powder Technology, 23(2012) 566-579

[8] I.Oldal I.Keppler B. Csizmadia L.Fenyvesi "Outflow properties of Silos: The effect of arching " Advanced Powder Technology 23(2012) 290-297

[9]R.Beverloo" The flow of granular solids through orifices" Chemical Engineering Science 15(262) (1961)

[10] J.R Johanson"Method of calculating rate of discharge from hoppers and bins "SME of AIME,Transactions 232 (1965) 69-80

[11] J.Mellmann ,T.Hoffmann ,C.Fürll "Mass flow during unloading of agricultural bulk materials from silos depending on particle form,flow properties and geometry of the discharge opening "Powder Technology 253 ,46-52 (2014)

[12] J.J McCarthy "Perspectives: turning the corner in segregation Powder Technology192,137-142 (2009)

[13] P. Tang and V.M. Puri (2004) " Methods for minimizing segregation :a review " Particulate Science and Technology 22,321-337

[14] B.Remy J.G .Khinast B.J.Glasser 2011 " Polydisperse granular flows in a bladed mixer: Experiments and simulations of cohesionless spheres" Chemical Engineering Science 66, 1811-1824

[15] M.Saad, A.Sadoudi ,E.Rondet B.Cuq " Morphological characterization of earth powders : How to characterize the shape of the particles " J.Food Engineering 102(2011) 293-301

[16] M.Dlier Rasul ,Modeling and Analysis of Gravity Driven Granular Discharge Ms Thesis University of Gaziantep ,2015

[17] M.O.Carpinlioglu , M.Dlier Rasul "Influence of material properties and storage modeling on discharge characteristics of a gravity driven silo " ICAME 15 Yıldız Technical University Poster Presentation, May 2015 Istanbul Turkey