Powder Technology 277 (2015) 252–261

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Pipe stability in aerated silos

Diego Barletta, Massimo Poletto

Dipartimento di Ingegneria Industriale, Università di Salerno, Via Giovanni Paolo II, 132, I-84084 Fisciano, SA, Italy

ARTICLE INFO

Article history:
Received 23 December 2014
Received in revised form 27 February 2015
Accepted 7 March 2015
Available online 16 March 2015

Keywords:
Piping
Rathole
Cohesive powders
Silo discharge
Aeration

ABSTRACT

The procedure to calculate the pipe stability criterion in aerated silos proposed by Johanson (2004) has been discussed and extended beyond the calculation limits present in the original paper. A table of the dimensionless function $G(\phi, A) = D_p g \rho_b / f_c$ has been calculated for angles of internal friction ϕ between 35 and 70° and dimensionless radial pressure gradients $-A$ between 0 and 10. Values of G in this table have been fitted with an algebraic expression which is able to correlate values with an approximation not larger than 10% and generally smaller than 3%. Theoretical findings were compared with previous experiments. The comparison between the theory and the experimental results indicates that aeration can produce significant changes in the effective body force acting on the powder to such an extent that the horizontal gas pressure gradient is larger than gravity and, therefore, beyond the limits provided by Johanson (2004). The theoretical approach is able to provide results which correlate reasonably well with the experiments if the appropriate bulk solid consolidation is used. In particular, if aeration is started before pipe formation, it can produce bulk solid compaction that increases pipe stability and has to be accounted for so as to evaluate critical aeration conditions for pipe stability.

1. Introduction

Silo discharge of cohesive powders may be hindered by the formation of arches and pipes. Piping occurs when a vertical channel (also called pipe or rathole), crossing the stored bulk from the outlet, at the silo bottom, up to the free surface of the stored material, is formed. Pipe may form when the inclination of the hopper is not steep enough to guarantee mass-flow and when the outlet size is too small. Flow aid devices, such as aeration pads, are commonly used in the industry to achieve proper flow of cohesive materials.

When piping occurs, the strength of the consolidated material in the dead zones exceeds the load stress and a stable pipe is formed. In this case the silo cannot be completely discharged. The design of a proper channel-free silo requires both the evaluation of the critical load stress condition in the material and the estimate of the material strength.

Jenike [1] and Jenike and Yen [2] determined the hoop stress on the channel wall as the most critical and proposed a relationship between the diameter of a stable pipe, the silo outlet size and the circumferential stress of the bulk solids around the pipe. Their analysis is based on the estimate of the pipe hoop stress with the hypothesis that the bulk material close to the pipe is at the limit of the plastic deformation. More details of this approach are provided in the next section. Hill and Cox [6], without proposing an alternative procedure, discussed on some aspects of the integration procedure followed by Jenike [1].

One of the main assumptions of the Jenike [1] theory is that the solution is sought at high depths at which there are no significant changes in the vertical direction. In order to overcome this limit Matchett [3,4] proposed a force balance on volume elements defined by hemispherical surfaces. Theoretical stress distributions are consistent with respect to wall stress [4], but deserve further experimental validation with respect to the estimate of the critical conditions for pipe formation.

Completely different is the approach proposed by Drescher [7] and developed by Drescher and Vgenopoulou [8] that is based on the so-called upper bound collapse theorem. According to this theorem, by equating the rate of energy dissipated in the velocity field and the rate of external work, an upper bound to the load inducing collapse or a lower bound to the load resisting collapse is obtained. Similarly to the theory proposed by Matchett [3,4], the results of the Drescher and Vgenopoulou [8] theory suggest a depth dependence of the pipe stability.

In order to estimate the material strength two different approaches can be followed. A less conservative approach was proposed by Jenike [5], according to whom the material at the pipe wall consolidates through the effect of the moving material inside the channel. A more conservative approach was followed by Johanson [9], according to whom the powder consolidation occurs during silo filling and, therefore, the corresponding value of the consolidating stress can be calculated following the Janssen [10] procedure. Roberts [11] recognized that the former approach can underestimate the pipe-free outlet diameter while the second is extremely conservative in a design procedure and, therefore, he proposes to calculate intermediate values of the consolidation stress. An experimental validation of this approach was provided by Jongejan [12].

E-mail address: mpoletto@unisa.it (M. Poletto).

http://dx.doi.org/10.1016/j.powtec.2015.03.009
0032-5910/

Under the hypothesis that consolidation occurs during silo filling, another issue regarding the material consolidation can be recognized. It concerns the fact that in this case the consolidation direction is vertical while the hoop stress direction is horizontal. Roberts et al. [13,14] suggest to account for this effect by using the Jenike tester [1,5,15] to evaluate the flow function and to rotate the sample of 90° between the preshear and the shear phase. Cannavacciuolo [16] and Schwedes et al. [17] on the basis of specific experiments carried out on a silo centrifuge, suggest a proper evaluation of the material anisotropy due to the shear direction with the use of a biaxial shear tester.

The interaction between the interstitial air and the solid discharge was verified by Crewdson et al. [18], and related to the local pressure gradient by Nedderman et al. [19]. Donsì et al. [20] verified the experimental distribution of gas pressure inside a hopper in the different phases of the silo discharge. The effective mechanism of interaction between solid discharge and gas pressure distribution was hypothesized by Barletta et al. [21]. The air flow in a mass flow aerated silo was suggested and modeled by Gu et al. [22]. Ferrari and Bell [23] and Lu et al. [24] observed the effect of aeration on the solid rates from hopper. Predictive models on the solid discharge rates were proposed by Donsì et al. [25] for fine powders and by Barletta et al. [26] for cohesive powders. The effect of aeration on cohesive powder arching was measured and modeled by Cannavacciuolo et al. [27]. Lu et al. [28] provided further experimental results on the discharge of pulverized coal from a pressurized hopper.

The effect of aeration on piping was modeled by means of a stability analysis by Johanson [29]. In that paper, however, the maximum value of pressure gradient determined by the aeration is limited by the adopted procedure for the numerical solution. This paper aims at extending the range of the explored pressure gradients beyond the limits proposed by Johanson [29], to provide a fitting equation to rapidly determine the critical pipe conditions and to provide an experimental verification of this theory.

2. Theoretical background

The theory by Johanson [29] is based on the evaluation of the critically stable conditions, that is the condition at which the pipe is on the verge of its failure. Under these conditions it is possible to apply the typical Mohr–Coulomb plastic deformation closure condition to the stress balance equation. According to this closure condition, the Mohr circle describing the stress state in the material on the principal planes is always tangent to the linear Coulomb yield locus, the physical implication being that the bulk solids are on the verge of internal shearing. This approach leads to an ordinary differential equation for the angle ω between the minor principal direction of stresses and the horizontal direction as defined in Fig. 1. The differential equation is a function of the dimensionless coordinate, η, defined as follows:

$$\eta = \left(\frac{2r}{D_p}\right)^2. \tag{1}$$

The distribution of ω is a function of the derivative at the boundary $\partial\omega/\partial\eta|_{\eta=1}$ and of the static angle of internal friction ϕ. The derivative at the boundary is important because it is related to the hoop stress on the pipe surface by the equation

$$\sigma_a = \frac{g\rho_b D_p}{4\left.\frac{\partial\omega}{\partial\eta}\right|_{\eta=1}} \tag{2}$$

where g is the acceleration due to gravity, ρ_b is the solid bulk density, and D_p is the pipe diameter.

According to Jenike [1] a physically suitable solution for instability (the instability is assumed with the Mohr–Coulomb closure condition) requires a “bounded” solution or, in other words, a solution that is independent of what happens at the periphery of the silo. This agrees with the observation that shape and pipe stability depend only on the outlet size and on the powder properties and not on other silo geometrical properties. The condition for a bounded solution to exist is the attainment of vertical shear planes, parallel to the pipe walls, in the material within the silo and somewhere around the pipe. As it appears from Fig. 1, the occurrence of vertical shear planes is attained if it is:

$$\omega_{max} = \frac{\pi}{4} - \frac{\phi}{2}. \tag{3}$$

The conclusion of the reasoning proposed by Jenike is subtle, a sort of a *reductio ad absurdum* approach. In fact, solutions for which the boundary conditions are such to produce unbounded solutions $\omega < \omega_{max}$ everywhere do not have a physical meaning and, therefore, contradict the Mohr–Coulomb plastic deformation conditions. These solutions correspond to stable pipes which are produced by unknown states of stresses within the material. On the other hand, the attainment of a bounded solution indicates instability and corresponds to non-observable powder states. Therefore, the only condition in which the

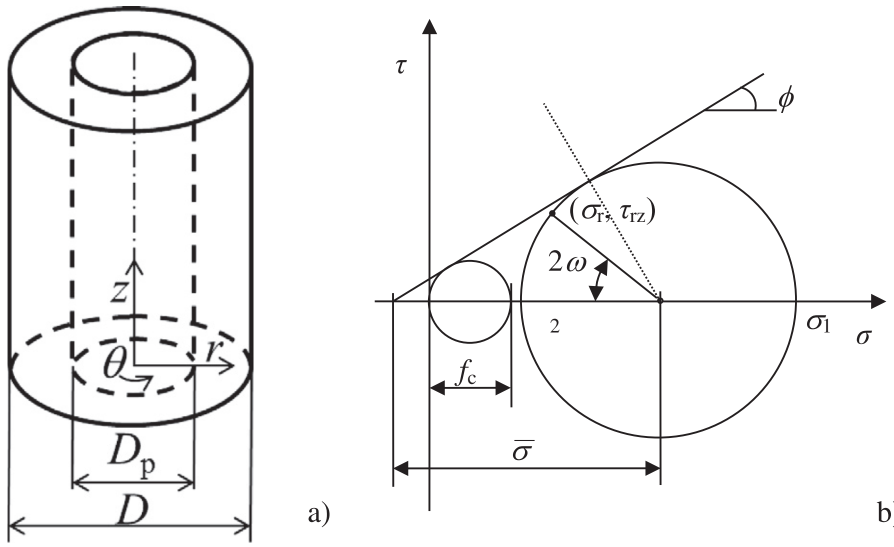

Fig. 1. Geometry and coordinate system in the silo (a). Coulomb yield locus (b).