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Original Research Paper

Outflow properties of silos: The effect of arching

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ABSTRACT

Engineers working on the field of agriculture, food- or pharmaceutical industry or in the architecture frequently meet problems arising from the special properties of granular assemblies. Storing large amount of particulate raw materials is mostly made by using large containers, called silos. The design of such large silos is far not an easy problem. The outflow properties are one of the most important parameters of silo design. The constant discharge rate of silos differs from the discharge rate of containers filled with liquids. In case of fluids, the flowing velocity and discharge rate changes with fluid level. In case of granular materials, the velocity is constant (independent of the filling level of silo). There are methods used for the determination of silo discharge rate, but these are mostly experimental without physical explanation of the phenomenon. In this paper we demonstrate that the constant discharge rate is caused by the formation and collapse of arches in the bin. Based on this assumption, we derive an equation for determining the discharge rate. Using the same arching hypothesis we derive the equations describing the velocity distribution at silo outlets. The usability of our new approach is demonstrated by experimental investigations.

1. Introduction

The special mechanical behavior of granular assemblies complicates the engineering design process of silos. Granular materials sometimes can be modeled as solid bodies, sometimes as liquids, but there are cases, when none of these two models can be used. One of these cases is the modeling of the outflow of granular materials from silos [1–3]. Unlike the fluids, the outflow rate of silos is constant (independent of the height of material above the outlet).

Beverloo [4] and Johanson [5] evaluated the outflow rate of silos for different cases. Beverloo's empirical law for silo discharge rate is

$$W = 0.58\rho\sqrt{g}\sqrt{(d-kd_p)^5}, \tag{1}$$

where W is the discharge rate, ρ is the bulk material's density, g is the gravitational acceleration, d is the outlet size, k is a constant (in most of the cases $k = 1.4$ is used) and d_p is the particle size.

Beveloo's law is the most accepted for predicting the outflow rate. This law has been tested for mono-sized particles where $d_p << d$ in [6]. If the outlet diameter is smaller than a critical value, the flow type will be the so called jamming flow [7]. The equation describing the discharge rate has two empirical coefficients. The effect of these coefficients has been examined by [8,9].

Beverloo's law is a very robust empirical method but it is unable to explain the physical process causing the phenomena (the constant discharge rate). We developed a new model for the outflow process, based on the assumption that the constant discharge rate of silos is caused by the formation and collapse of arches in the bin. The arch formation and collapse causes the pulsation phenomenon found by [10]. Research based on experiments and discrete element method simulations on the silo outflow problem is in progress [11,12]. This also shows the importance of the topic of our research. We show here, that some questions still can be answered using only analytical methods.

2. Flow patterns

Because of its crucial effect on the stress and flow properties, the flow pattern is an important parameter from the design point of view. The different flow patterns can be seen in Fig. 1. Case *a* is the so called funnel flow, when first that material flows out from the silo, which is above the outlet.

In this case, the material lying in the upper layer comes into motion during outflow. The other type of outflow is the so called mass flow (Fig. 1. case *b*), when all of the material stored in the silo comes into motion [13]. In this case, all the material moves together towards the outlet. The formation of the two characteristic types of outflow depends mostly on the bin half angle and the wall friction coefficient [14].

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