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SOME NOTES ON ENGINEERING MODELS OF VIBRATIONAL SIZE-CLASSIFICATION OF GRANULAR MATERIALS: IMPROVED PRESENTATION OF IN-LAYER SEPARATION PROCESS, SCREENING OPTIMIZATION.

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Abstract. *Vibrational size-classification of granular materials is a process of indisputable importance in mining engineering, waste processing and a lot of other industries. Despite the three hundred year history of the technology it has not been developed yet well balanced screening models. Modern engineer's inventory contains resource intensive all-purpose computational models (like DEM), which are sometimes of almost no advantage of full scale modeling, and lots of empirical formulae derived for certain particular conditions which are of no use when the conditions are not met i.e. unsuitable for significantly unconventional devices.*

The model presented in this article is aimed at filling the gap between numerical and empirical approaches where the first ones are too slow and the second ones are fairly inaccurate. The goal is achieved through customization of a number of analytical models for numerical simulations. Additionally some improvements in presentation of intralayer vibrational size separation were made.

Because of its computational simplicity the presented approach allows to perform numerical optimization on vibration screens parameters such as the sieve metrics, vibration frequency etc.

1 INTRODUCTION

Screening is vital for the preparation of mineral resources for the dressing process. These operations directly account for 4% to 6% of the total electricity consumption for disintegration. In addition, quality screening processes directly reduce energy consumption in open and especially in closed circuit crushing, since the aggregate loading of energy-intensive crushing equipment directly depends on the accuracy of grain-size classification. Therefore, correct calculation and selection of controlled screening parameters and screen designs ensure actual energy savings in processing of all types of raw materials. Moreover, when processing non-metallic minerals and coal, they ensure high commercial quality of the final products.

Rapidly developing numerical optimization methods appear to become a very efficient tool for engineering analysis. These methods allow estimating proper design factors of various devices and machine parts, provided appropriately tuned numerical model of the objects under investigation is given. Taking into account the fact that computational optimization methods demand for numerous evaluation of their goal function, it is worth using as fast and simple basic process simulation algorithm as possible against the background of precise enough modeling. Compromising the controversy, one of engineer's most important tasks is often to find out which of existing models of the process could fit better.

2 CURRENT STANDING

There are three essential branches in screen separation modeling: empirical approaches, phenomenological and numerical ones. Empirical models based on experimental data aim usually to predict the required area of screens. Furthermore, these reductive schemes are notably attached to the device architecture and working conditions they were derived for. Phenomenological models incorporate certain theories of the screening process. These are either probabilistic or kinetic theories. Application of such models has not become a frequent practice for sometimes they were both remarkable sophisticated and not too advantageous in terms of precision. Numerical models are based on computer solution of Newtonian mechanics. I.e. these models are exhaustively universal but demand for sufficient preliminary preparation (including natural calibration experiments) and extensive computational resources and simulation time. All-purpose numerical approaches such as discrete element (DEM) or particle dynamics models could not often surpass natural experiments in labor-output ratio.

Notable advances in computing hardware could not still resolve all the drawbacks of DEM-like approaches and make them applicable for area covering multiple simulations. But these advances are good enough to facilitate application of phenomenological approaches by confining their intricacies in the program code. Thus it becomes apparent that even more benefits could be gained as a result of further improvements in computational application of such methods.

3 IMPROVED KINETIC MODEL

In this article, authors put forward a phenomenological approach improving and generalizing a group of kinetic methods. Some early versions of this approach were presented in [1, 2]. The skeleton of the model is based on the treatise [3] suggestions (generalizing well known [4, 5] approaches) but modified to fit for computer simulations. The granular material is given by its granulation (a predefined proportional mixture of a set of narrow classes of d_i particle diameter), apparent (bulk) density (ρ) and its friction properties (μ – dry and λ – instant friction coefficients ideally for both particle-screen and particle-particle interactions). The following parameters are taken into account for the screening area: linear dimensions (l – length and a – width), slope angle (α), openings diameter (d_0), effective area (φ) and characteristics of vi-

bration (A and B – horizontal and vertical amplitude components, ω – phase rate and type – either linear or elliptical). The flow of the granular material is considered to be flat and its on-sieve layer is virtually dissected into a group of rectangular cells $\Delta y \times \Delta x \times a$ (see Figure 1). A set of properties including granulation ($F_{k,l}(d_i)$ represents the part of the class d_i in the cell indexed $[k, l]$) and material outflows is stored for each computational space-cell and column.

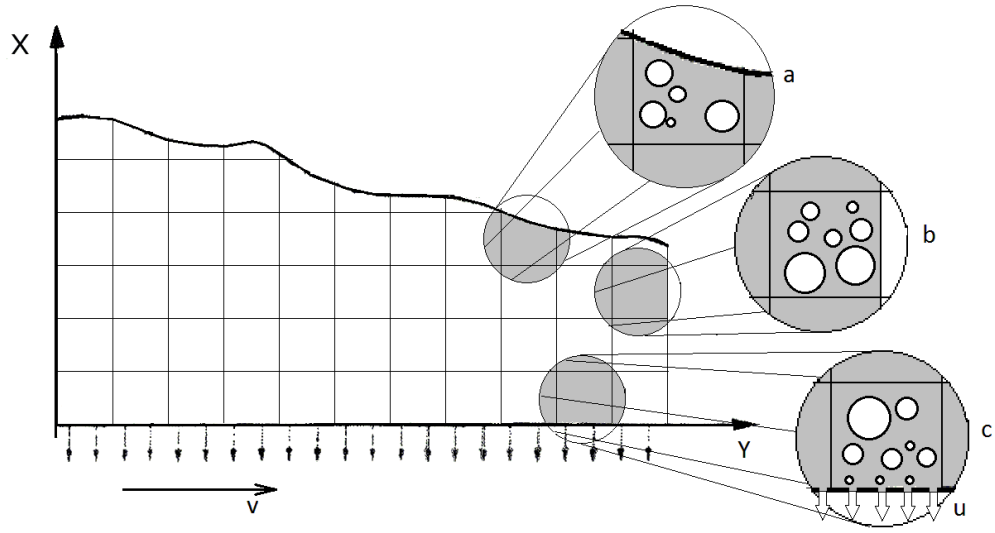

Figure 1: Longitudinal section of a material layer on the screen, cell distribution a) surface cell, b) material package cell, c) cell of the contact area between the material and the screen.

It appears reasonable to consider vibration screening process as a combination of three comparatively independent phenomena: vibratory displacement of the material layer, a process of passing of material particles through the openings in the screening surface and rearrangement or vertical migration of particles inside the layer. The main loop of the simulation steps thus through the columns of the computational cells. The material is considered to stay in the column for a time Δt determined by Δy length and the velocity of vibratory displacement of the material on the relevant part of the screening surface (V calculated via separate submodel [6]). For each column the iteration of the loop begins with calculation of the mass-outflow of granular material through the sieve openings. Then the material particles in the column are redistributed simulating their natural intralayer migration. And then the resulted column of granular material moves one position in the mesh to the dumping area.

3.1 Outflow submodel

As in generic approach the rate of the outflow for the narrow class d_i through the segment of the sieve with index k could be calculated by the following formula:

$$q_k(d_i) = P(d_i) u F_{k,0}(d_i) \Delta y a, \tag{1}$$

where $P(d_i)$ is the "probability" for a particle of the class d_i to pass the sieve opening, u is a constant characterizing the velocity of the passing particles and $F_{k,0}(d_i)\Delta y a$ determines the quantity of the class d_i in the material-sieve contact area. Originally, $P(d_i)$ was calculated using Gaudin's formula:

$$P(d_i) = P^{d_0}(d_i) = \varphi \left(1 - \frac{d_i}{d_0}\right)^2. \tag{2}$$

But the formula does not take into consideration the possibility of paired particles to pass the opening. An improved formula was proposed in the article [7] that could be transformed to be used in the algorithm and takes the following form:

$$P(d_i) = P^{d_0}(d_i) + \sum_{j,(d_j+d_i \le d_0)} F_{k,0}(d_j) P^{d_0}(d_j) P^{d_0-d_j}(d_i). \quad (3)$$

Moreover it is possible to derive a simple recurrent expression for this probability that takes into account the possibility of simultaneous passing of any combination of particles:

$$P(d_i) = \tilde{P}^{d_0}(d_i) = \begin{cases} P^{d_0}(d_i) + \sum_j F_{k,0}(d_j) P^{d_0}(d_j) \tilde{P}^{d_0-d_j}(d_i), d_i < d_0 \\ 0, d_i \ge d_0 \end{cases} \quad (4)$$

3.2 Intralayer processes

The other important phenomenon included in the model is the process of vertical migration of particles. All processes occurring inside the material layer during its vibratory displacement may significantly influence the sieve classification process, as they determine granulation of particles in contact with the screening surface. There exist various mathematical descriptions of these processes in vibration screening simulations mentioned in numerous studies [5, 8]. It is known that particles of homogeneous material tend at once to mix up and separate in layers by size under vibration. So the first draft-quality approach dealt with these effects as a uniform processes proportionally averaging given granular distribution with mixed and separated ones. That approach has, however, a distinct drawback: in such a simulation, essentially inhomogeneous materials are sorted at the same rate as almost homogeneous materials. For this reason, the algorithm was completed with an improved model representing separation as part of the material exchange between computational cells (Figure 2). Such an exchange may be due to granular convection or otherwise generated random movements of particles in the granular media; when shaken, small class particles tend to pass between large particles blocking them. That is, small class particles are screened through a layer of larger particles, as if through a sieve.

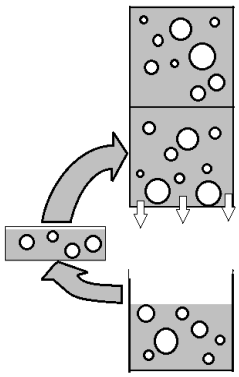

Figure 2: Material flow between cells in separation simulation.

In improved separation modeling, the lower boundary of each cell represents a conventional screening surface with an opening diameter equal to the gap size between packed particles of a radius average for the cell. Let us denote the average particle radius in a cell $\tilde{R}$, then the opening diameter of a conventional screening surface with dense packing is

$$\tilde{d} = \left(\frac{2\sqrt{3}}{3} - 1\right)\tilde{R}, \tag{5}$$

and its useful area is

$$\tilde{\varphi} = \frac{\left(2-\sqrt{3}\right)^2}{3\sqrt{3}}\pi \tag{6}$$

These formulas were also amended with regard to the fact that shaking produces additional gaps between material particles. If average particles are removed from the dense package by the distance of Δr, the amended formulas shall be as follows:

$$\tilde{\tilde{d}} = \tilde{d} + \frac{2\sqrt{3}}{3}\Delta r, \tag{7}$$

$$\tilde{\tilde{\varphi}} = \tilde{\varphi} + \frac{\left(4-2\sqrt{3}\right)\tilde{R} + \left(4-\sqrt{3}\right)\Delta r}{3\left(\tilde{R}+\Delta r\right)^2}\pi\Delta r \tag{8}$$

Therefore, small classes get an advantage in terms of access to the screening surface, which enables more realistic extraction curves.

4 EXPERIMENTAL VERIFICATION

Table 1 shows comparative results of modelling and field experiments for three versions: original, improved screening and improved separation versions. The extraction curves shown in Figure 3 for field and numerical simulations using the original and improved methods correspond to the first experiment in the table.

					Recovery rates			
	Feed material grain-size classes (mm)	Grain-size class content (%)	Mass screening capacity (t/h)	Sieve cell size (mm)	Experimental data	Original model	Improved screening	Improved separation
1	-0.071+0	1.6721	1.7612	0.6300	0.8333	0.9737	0.9626	0.9840
	-0.18+0.071	11.4054			0.9091	0.9720	0.9604	0.9509
	-0.315+0.18	8.5752			0.8750	0.9669	0.9540	0.8610
	-0.63+0.315	16.7392			0.5319	0.8448	0.8196	0.6064
	+0.63	61.6080			0.0000	0.0000	0.0000	0.0000
2	-0.071+0	1.2631	0.6263	0.6300	1.0000	0.9784	0.9690	0.9910
	-0.18+0.071	11.1155			1.0000	0.9779	0.9684	0.9688
	-0.315+0.18	8.8419			1.0000	0.9766	0.9666	0.8995
	-0.63+0.315	17.1158			0.6923	0.9504	0.9348	0.7241
	+0.63	61.6637			0.0000	0.0000	0.0000	0.0000
3	-0.071+0	1.2405	0.5374	0.3150	1.0000	0.9659	0.9515	0.9629
	-0.18+0.071	11.1700			0.9885	0.9637	0.9487	0.9028
	-0.315+0.18	10.3020			0.7419	0.9251	0.9030	0.7469
	-0.63+0.315	16.5616			0.0000	0.0000	0.0000	0.0000
	+0.63	60.7259			0.0000	0.0000	0.0000	0.0000
4	-0.071+0	1.5283	1.7250	0.3150	0.8889	0.9594	0.9430	0.9523
	-0.18+0.071	11.9831			0.8657	0.9509	0.9325	0.8779
	-0.315+0.18	8.5949			0.6129	0.7682	0.7376	0.6118
	-0.63+0.315	17.0231			0.0000	0.0000	0.0000	0.0000
	+0.63	60.8706			0.0000	0.0000	0.0000	0.0000

Table 1: Comparison of field and numerical modelling results (using different approaches).

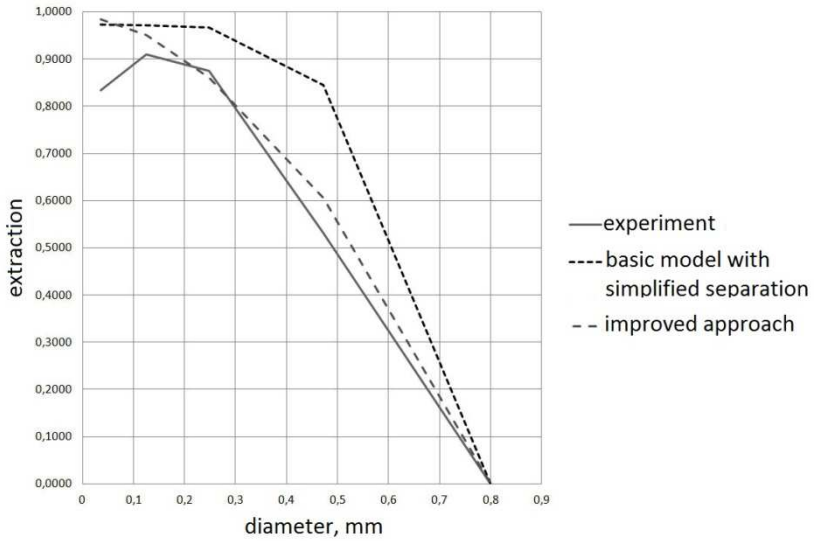

Figure 2: Extraction curves for various grain-size classes.

5 CONCLUSIONS

The vibration screening modeling approach presented in this paper has several advantages as compared to both up-to-date numerical and most common analytical methods. It enables high accuracy modeling without a time-consuming setup, calibration and preliminary experimental preparations, and may be applied for a wide range of devices. This approach was used as the basis for a computer program with a friendly user interface that enables designers to evaluate future operation of the device designed based on its input parameters. And because of low resource-intensity of calculations the program was equipped with Particle Swarm Optimization module that allows preliminary assessment of optimal parameters for new screening devices provided acceptable range of the design parameters.

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