Performance Prediction and Optimization for Industrial Sieves by Simulation: a two-tier Approach

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We present a numerical study of sieving behavior on industrial sieves, composed of several vibrating screens, a process widely used in diverse industries. The modeling approach is twofold: on the one hand, particle flow is modeled in some detail by means of a discrete element model (DEM). This allows studying the influence of various parameters on the behavior of individual particles, particularly transport velocities and collision rates. Computational complexity however forbids the simulation of an entire sieve as a DEM. Instead, the overall sieving behavior is modeled separately by means of a more phenomenological model, the so called thick layer model (TLM), which is based on mass-balance equations, that translate into an ordinary differential equation. The TLM obtains its most crucial input parameters as results of the DEM. Comparison of simulation results with measurements shows, that this combined approach is capable of accurately describing the sieving process at a reasonable computational cost.

1 Introduction

Sieving or screening is the standard operation for the classification of particles according to their size, used in many industries. Experimental investigation of this process dates back to at least the middle of the 20th century, e.g. [8, 10]. The intricate dependencies of the sieving quality on various parameters (e.g. oscillation amplitude, frequency and sieve inclination) that were found, incited an interest in model-based studies Existing models can be divided into those that are essentially based on the theory of stochastic processes and those relying on discrete element (DEM) simulations. Interest in the latter seems to receive new momentum with the increased availability of computing power in recent years, e.g. [4, 11] and others, see below. A widely used model is from Standish [13].It is based on the simple assumption that screening is a first-order process. This means that the material on the screen falls through the mesh with a constant rate, giving rise to an exponentially falling function of time, respectively of distance travelled along the mesh. The work of Andrzejczak and Wodzinski [3] is similar in assuming that passage through the mesh happens as a first order process with constant rates to be determined experimentally. In addition, they try to model the effect of a thick bed by assuming that only those particles can fall through the mesh that are in a so-called discharge layer of some given thickness, directly above the screen. The model of Sultanbawa et al. [14] is another macroscopic approach which is based on constant rates and mass balances. Instead of fitting the rates, the focus is on a related parameter q, the ratio of concentrations of undersize particles in the inlet and overtails streams. The theory is applied to a cascade of sieves and a graphical technique is developed to predict the concentration of fines with time. With the rapid progress in computer efficiency, microscopic modeling and simulation techniques have become popular in the last 10 years. The idea is to model individual particles and their interaction among each other and with the screen and to numerically follow their trajectories. The different sub-classes of such an approach, such as event driven rigid particle mechanics, molecular dynamics, direct simulation Monte Carlo, or lattice models are described in detail in a review paper by Herrmann [9]. Most often, the discrete element method is applied to screening simulations. In two recent publications, this method is applied to a tumbling sorting machine by Alkhaldi [2] and to a multi-deck banana screen by Dong et al [5]. A three dimensional DEM model of a vibrating screening process is developed in [4] to study effects of amplitude, frequency and angle on screening quality and to develop empirical formulae to link particle-deck collisions with these parameters[1] The advantage of such a microscopic approach lies in the fact that the screening process parameters such as vibration amplitude and frequency, screen length and width, inclination angle, mesh size, and so on, are part of the model and their influence can be studied. Nonetheless, the usability is still limited by the computational complexity of the task. [2] states, that the simulation of a screening process of 9900 particles, which takes 45 seconds in real time, takes about one week of simulation time.

2 Simulation Method

The aim of the present study is to combine the aforementioned advantages of DEM simulations with the flexibility and computational lightness of a macroscopic approach. For this purpose two separate models are used to describe the screening process: a simplified DEM and the macroscopic thick layer model (TLM). The screening parameters considered for the simulation are the inclination angle of the sieve, the oscillation angle, the oscillation amplitude, frequency and the load rate.

2.1 The Discrete Element Model

Several Open-Source DEM packages are available, e.g. (in no particular order) LMGC90 [6], SICONOS [1], YADE [12], as well as commercial packages like EDEM. We used YADE to simulate a stripe, about of 0.2m width and 5m length of a sieve deck with a continuous inlet of particles. The simulated length corresponds to an actual sieve. The reduction in width is justified by the fact, that particle velocity components across sieve width are very small. Rigid walls have been simulated along the edges of the stripe. The particles themselves were modelled as triangular pyramids, each composed of four balls. This allows simulation of non-spherical particle geometry (which would be the computationally simplest case) still at low computational cost compared to simulation of freeform-shapes. A snapshot of a simulation is shown in figure 1. Spherical particle geometry is used in e.g. [5], but in our simulations produced systematically too high transport velocities as compared to measurements. Particle size distribution can be set as a simulation parameter to correspond to the actual input on the real sieve, with particles mm – which in practice pass very quickly through the mesh - ignored. The simulated, vibrating screen is impenetrable for the particles: the purpose of the DEM is only to calculate transport velocities and collision rates in function of the parameters. The actual sieving simulation is the task of the TLM. The simplifications allow scanning the parameter space given in Table 1.

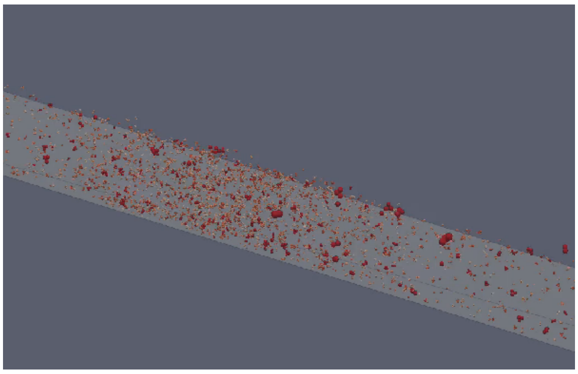

figure 1: Snapshot showing the motion of particles on a screen. The (tetrahedral) Particles are colored according to diameter. No actual sieve has been modeled, i.e. particles cannot fall through the screen.

2.2 The Thick Layer Model

A sieve consists of several decks with meshes of different sizes. A schematic representation is given in fig. 2. Material is transported from top left to bottom right and should fall into the bag according to size, with bag sizes increasing from left to right. For the simulation each deck is divided into a number of cells and the

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[1] in the entire paper, *collision* refers to a collision between a particle and a sieve deck.

Incline Angle [deg]	0	5	10	15	20
Amplitude [mm]	2	4	6	8	10
Oscillation Angle [deg]	0	5	10	15	20
Frequency [rpm]	800	900	1000	1100	1200
Load rate [t/h]		140	230	320	

table 1: Parameterspace for DEM Simulation. All the possible parameter combinations have been simulated by the DEM.

amount [kg] of matter per fraction and cell is the state variable of the model. Under some simplifications, the relative error in due to the discretization into cells can be shown to be of order (by passing to the corresponding PDE without discretization) and can be chosen to keep this error within a few percent. The sieve must classify the matter according to size into a number of bags, the diameters that should fall in one particular bag form a so called fraction. The flow on the sieve is then modeled as an ODE

$$
\begin{aligned}
\frac{d\varphi_{i,j,n}}{dt} &= I_{i,j,n} - \left(\frac{v_{i,j,n}}{\lambda_{i,j,n}} + \sigma_{i,j,n} p_{i,j,n}\right) \varphi_{i,j,n} \\
&+ \frac{v_{i,j-1,n}}{\lambda_{i,j-1,n}} \varphi_{i,j-1,n} \qquad (1) \\
&- \sigma_{i-1,j,n} p_{i,j,n} \varphi_{i-1,j,n}
\end{aligned}
$$

using the mass-balance. The interesting output is mainly the distribution of particle sizes in the bags in the stationary state.

Here, the index (i, j, n) refers to fraction n in cell j on deck i. φ [kg] is the mass, I [kg/s] is the input stream, v [m/s] is the transport velocity, λ [m] is the length of the cell, σ [1/s] is the mean collision rate with the sieve deck and p [-] is the (geometric) probability per collision of a particle of passing through the mesh. The parameters v and σ are calculated from the DEM and fed to the TLM as input. The ODE is nonlinear, since v and σ depend on the mass inside the cell. The geometric probability p of a particle passing through the mesh in one collision can be approximated as [4]

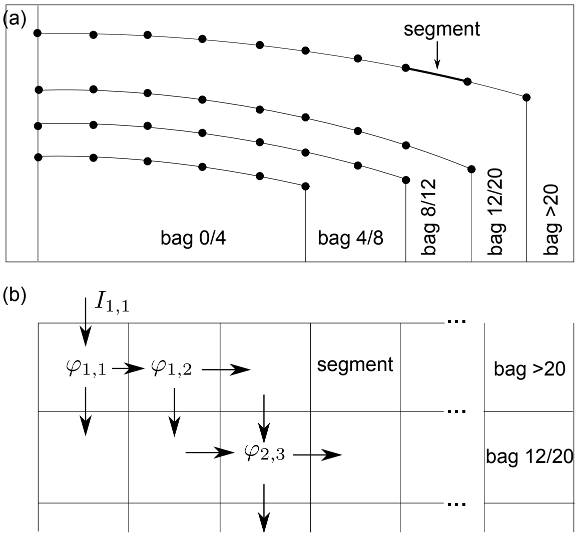

figure 2: Schematic representation of a sieve with five decks, each subdivided into several segments, (a) as simplified sieve geometry and (b) schematic. The state vector of the TLM is composed of the masses of each fraction in each segment. The equations governing the TLM are mass-balances of particles flowing in and out of each segment.

$$
p = \frac{(a-d)(\arccos(\theta)-d)}{(a+b)^2 \cos(\theta)} \qquad (2)
$$

where a, b and d are the sizes of the (rectangular) aperture and particle respectively and θ is the inclination angle. In our model, the particle size d is the mean diameter of particles in each fraction. The probability of one particle to remain on the screen after N collisions is then given by $p_N = (1-p)^N$. This is valid for individual particles, however as the particles progress along a sieve deck, the mean diameter d within a given fraction tends to increase (the smaller particles having already fallen through the mesh). Therefore a Weibull-Type distribution

$$
p_N = \exp\left(-(\mu/k)^N\right) \qquad (3)
$$

which takes this “ageing effect” into account has been found more adequate. This is illustrated in figure 3.

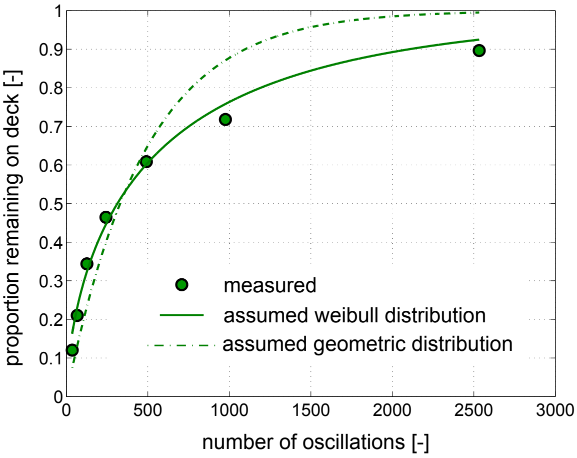

figure 3: proportion of particles of one fraction remaining on the deck after a number of oscillations. This proportion would follow a geometric distribution, if all particles were the same size (dash-dotted line). Since the proportion of larger particles rises with time, a Weibull-type distribution describes the measurement much better.

The additional parameters μ and k and can be calculated from the (Gaussian) size distribution within the fraction or simply fitted to measurements.

2.3 Computing time

All simulations were performed on a standard personal computer (Intel Xeon cpu, 2.27GHz) with a Linux-type (CentOS 6) operating system. The computationally expensive part is the DEM. Each of the 1875 possible parameter combinations from table 1 was simulated for 5s simulated time, which took in total one week of computing time. The results from this simulation are velocities und collision rates, which were sampled at 0.01s intervals during the simulations.

Once the DEM part is completed, the transport velocities and collision rates can be used as input for the TLM (interpolated between the simulated parameters if desired). The TLM is an ODE which can be solved via a standard solver in the numerical open-source package GNU Octave [7]. The simulation can be stopped, once a stationary state is reached, which is normally the case after less than two minutes simulated time, corresponding to only a few seconds computing time (on the same processor). This allows for a very fast estimation of sieve performance. The TLM simulations could also be performed e.g. during sales discussions at a potential customers site.

3 Measurements

Simulations were carried out under the real conditions of actual sieves, so they could be compared to field measurements of transport velocity and collision rate. The measurements were conducted on two sites by filming the stone on the top deck with a high-speed camera. Figure 4 shows the situation. The transport velocity can be assessed with good confidence. At 7° inclination and an amplitude of 5.25 mm, the mean value was measured as 0.3 m/s and at 19° inclination and 3.5 mm amplitude it was measured to be about 0.4 m/s. The collision rate is much more difficult to assess. The measurements indicate, that at typical parameter values there will on average be less than one collision per oscillation.

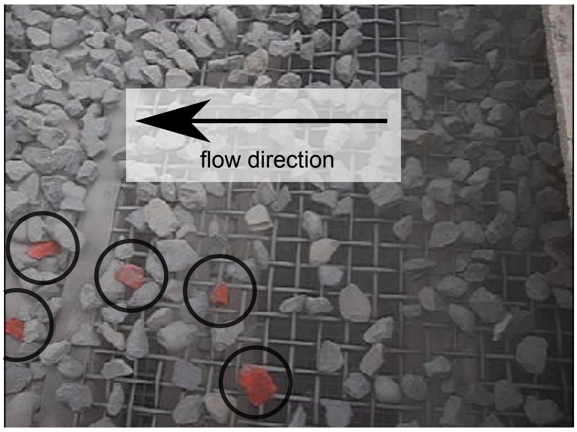

figure 4: Stone on the sieve as filmed during the measurements. The encircled stones entered the sieve at the same time and give an indication to the variability of the transport velocity.

Quality indicator for the sieving process are the amounts of under- and oversize, i.e. the amount of particles that are too small respectively too big for the bag they effectively landed in. Oversize can mostly be avoided by choice of an appropriate mesh size, thus undersize is the preferred quality measure. This quantity has a sharp bend when the load rate is increased over a critical point as illustrated in figure 5.

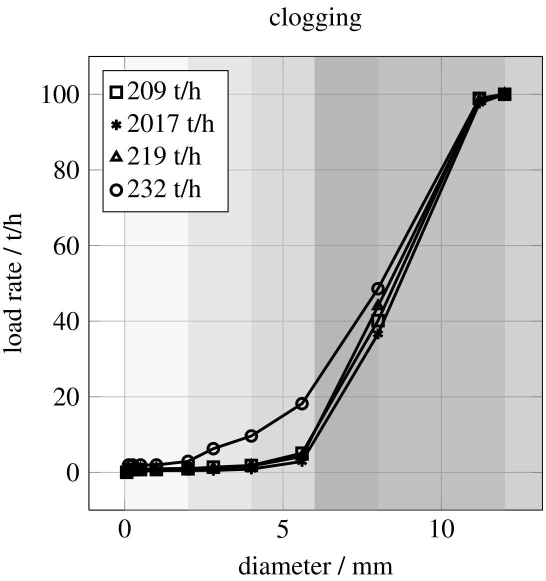

figure 5: Cumulative size distribution of the 8/12[mm] bag for different load rates. The distribution for 231.8[t/h] sharply differs from the lower load rates: at this load the bag contains much more undersize

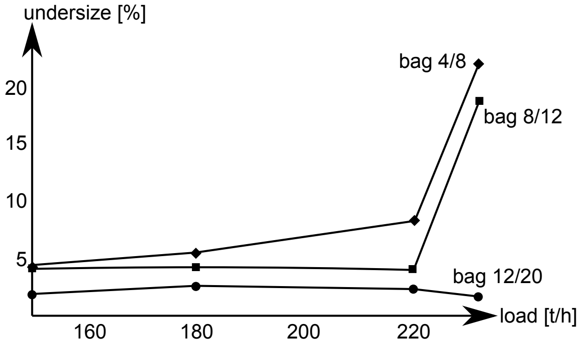

figure 6: Simulated undersize in three bags at different load rates. The qualitative behaviour, i.e. the sharp increase of undersize at a critical load rate is well reproduced by the model, the absolute quantities of undersize differ between measurement and model

4 Results

4.1 Model validation

Transport velocities and collision rates have been calculated for the parameters in table 1. The mean transport velocity is in good agreement with the measurement, as can be seen in figure 8, collision rates have not been measured.

This sharp bend of undersize at a critical load rate is qualitatively reproduced by the simulation as illustrated in figure 6.

To judge the overall agreement of the DEM/TLM model, we compared the cumulative distribution of particle sizes in the different bags, which showed very good agreement with the measurements, as is illustrated in figure 7.

4.2 Predictions

Intuitively, one expects good sieving quality at high collision rate/velocity ratios, thus maximizing the number of collisions per length. The influence of parameters on these values can be investigated with the DEM. Figure 8 shows projections to the frequency/amplitude plane at base values of the remaining parameters. Collision rate shrinks with growing amplitude and is less affected by frequency. Mean transport velocity grows with amplitude and frequency. However, more information than just velocities and collision rates are needed, to determine optimal sieving parameters. E.g. lowering the velocity can lead to an accumulation of particles which implies a reduction of the average number of collisions between the particles and the screen, because more particles will not touch the screen anymore. This effect is not fully captured by our DEM, since no sieve-mesh has been modelled.

Figure 9 shows the influence of amplitude, frequency and an inclination of the entire sieve on the percentage of undersize in one particular bag. This is a result of the combined DEM-TLM. Good choices for amplitude/frequency combinations are clearly distinguishable in the plot. Moreover the sieving quality for a given choice can be influenced through the inclination angle. It is thus possible to optimize, e.g. for realizing good quality with lower amplitude/frequency (i.e. smaller drive capacities) or for realizing consistently optimum quality over all bags.

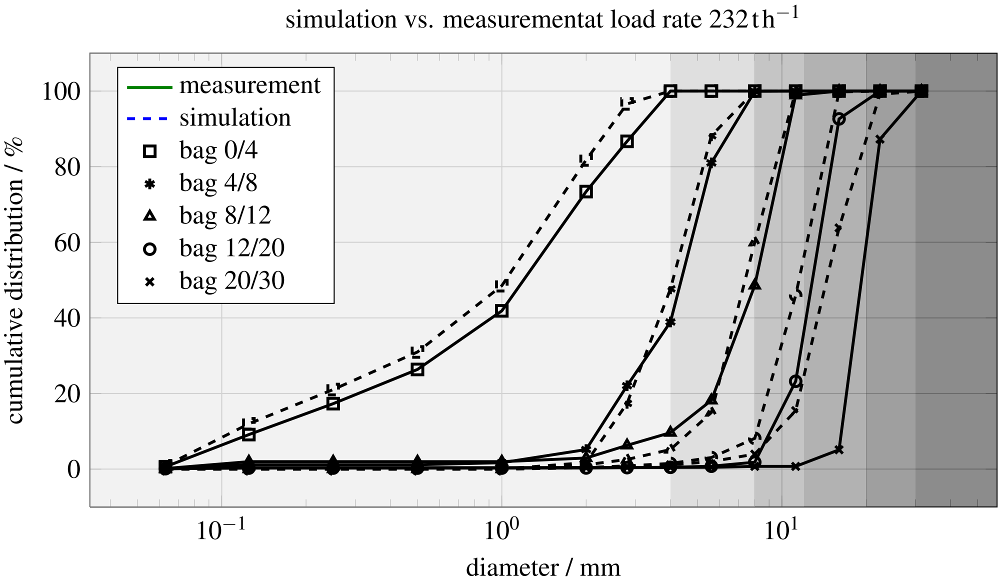

figure 7: Shown are measured and simulated data for bag 0/4, bag 4/8, bag 8/12, bag 12/20 and bag 20/30. The accumulated amount of particles with diameter x divided by the total amount, has been measured before and after the screening. It is compared to the accumulated distribution from the simulation. Each data pair corresponds to the output of a deck.

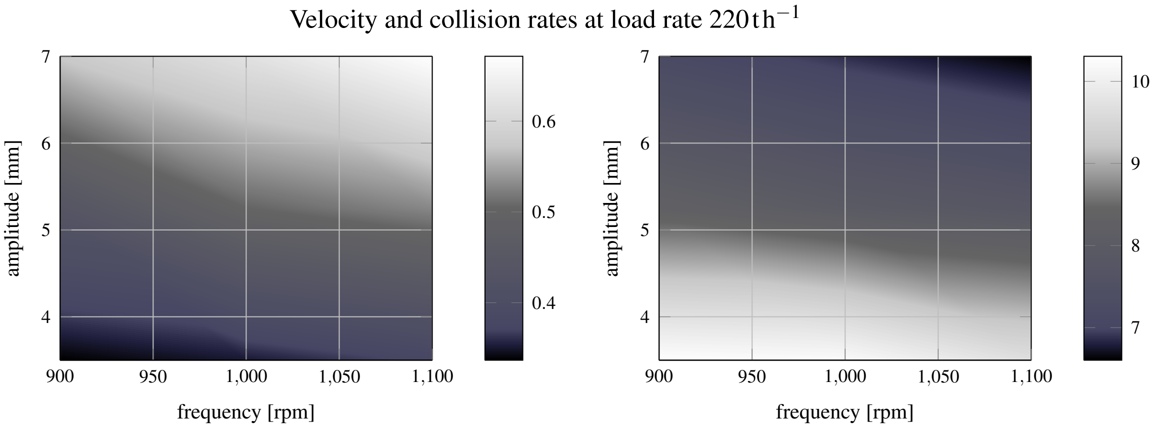

figure 8: transport velocities in m/s and collision rates in 1/s vs. frequency and amplitude as calculated by the DEM.

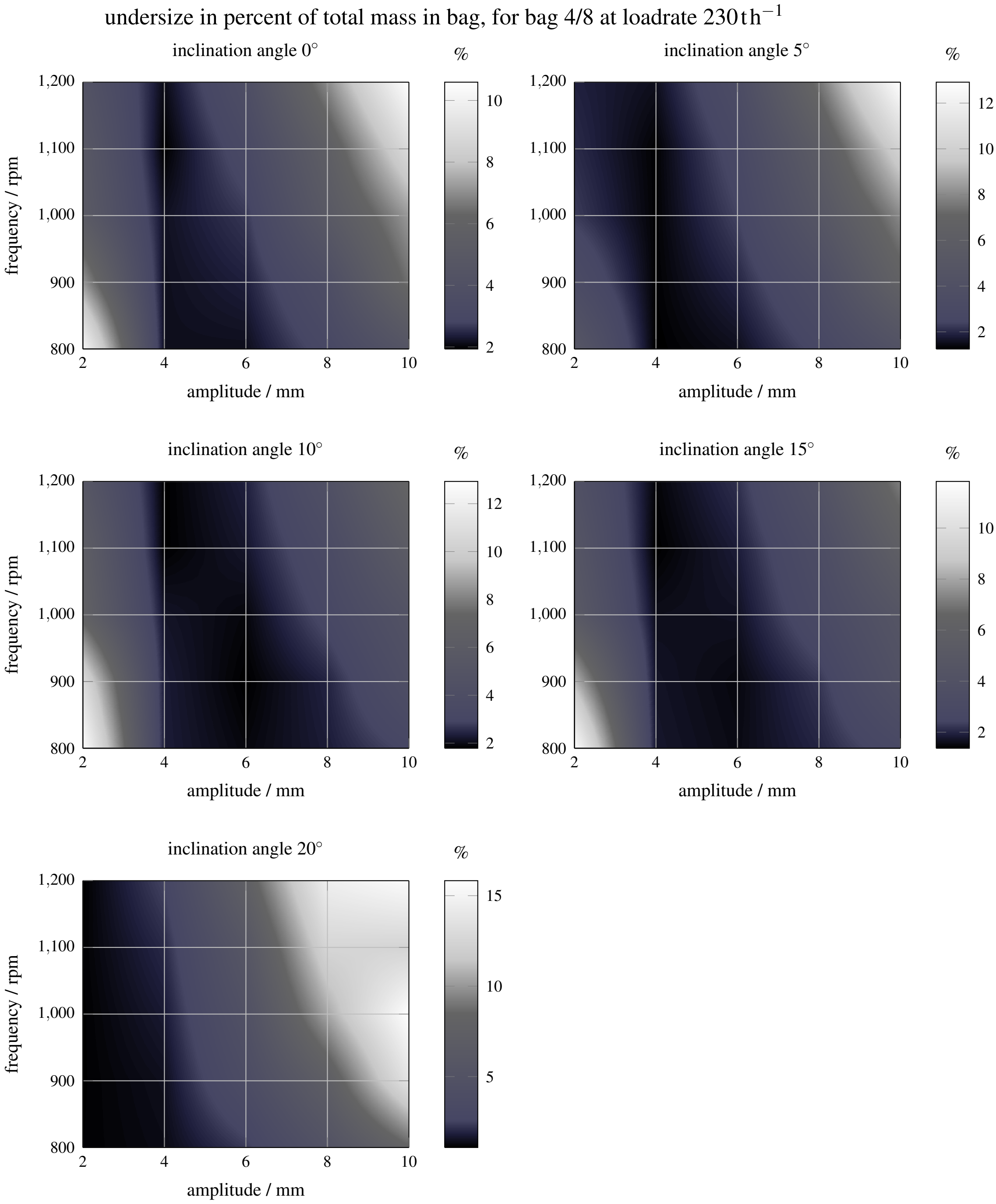

figure 9: Percentage of undersize in one bag vs. frequency and amplitude for different inclination angles. Here inclination angle refers to an inclination of the entire sieve in addition to the inclination of decks in the sieve.

5 Conclusions

A combined model approach composed of a microscopic (Discrete Element) model and a macroscopic (Thick Layer) model has been proposed to simulate vibrating screening processes. This two-tier approach to simulation permits to simulate an entire sieve at a modest computational cost, the entirety of the sieve being simulated by the computationally cheap thick layer model, based on inputs from the more expensive discrete element model, which in turn simulates only a representative but small excerpt of the sieve. Despite the simplicity of the approach, the result of the simulation is in good agreement with measurements done on real hot mineral screens in the field. A more complete validation will help to enhance some details of the model, but the tendencies that can be observed already with the actual model make it possible to detect interdependencies of the different parameters, and their influence on the screening result.

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