STUDY OF INFLUENCE OF VIBRATION PARAMETERS ON THE EFFICIENCY OF HORIZONTAL VIBRATING SCREEN USING THE DISCRETE ELEMENT METHOD

Mauro Sergio Vieira Matos, msvmatos@hotmail.com
Alexandre Luiz Amarante, Mesquita, alexmesq@ufpa.br
Fernando Pereira Mascarenhas, nando280@hotmail.com
Luiz Carlos da Silva Carvalho, lcsc@ufpa.br
André Luiz Amarante Mesquita, andream@ufpa.br

Federal University of Pará, Faculty of Mechanical Engineering, Augusto Corrêa St, 01, Zip-Code 66075-110, Belém-Pará, Brazil.

Abstract. Screening operations are used extensively in mineral processing so that there are several types of vibrating screens used for various applications. However, the mechanisms of particle motion and penetration behavior are not fully understood and they are still motive of research. In this context, this paper presents numerical simulations for the screening of iron ore spherical particles with 6mm diameters in a horizontal vibrating screen using the Discrete Element Method (DEM) in order to assess the influence of some vibration parameters (amplitude, frequency and throwing index) in the screening efficiency. The software commercial package EDEM from DEM Solutions was used to simulate the screening process. The simulations are carried out upon the recommendation from some guidelines presented in specialized literature. The results are used to formulate mathematical functions between the vibration parameters and the screening efficiency of the vibrating screens.

Keywords: Vibrating screen, Discrete Element Method, Numerical simulation
1. INTRODUCTION

Screening is an important means of size classification used on granular or particle materials, however the mechanism of particle motion and penetration behavior are not fully understood, and they are still motive of research.

The Discrete Element Method (DEM) is a numerical method suitable to calculate the mechanical behavior of granular medium. At the screening process, particulate material is classified by presenting it to a screen surface having apertures of a known size. To achieve efficient size separation individual particles must have many opportunities to pass through the screen aperture.

Much of the publication concerning the factors that affect screen efficiency is empirical in nature or attempts to establish optimum screening condition based on experiments. Among the major factors that influence the screening efficiency are the vibratory parameters, as these parameters change the way the particulates are presented to the screen deck. Thus, results obtained in machines with different vibration parameters set are in poorly agreement, even when using similar material and screen surface. Find a relationship between screen efficiency and vibration parameters can give a valuable insight for industrial screen.

Simulation studies based on DEM are currently widely used to study the particulate behavior over screen decks, which has been an effective numerical method used to characterize granular flow. To further understand the screening process at flat and inclined linear motion screen, numerical simulation of screen process using a 3D DEM model is presented in this paper. Based on the empirical early studies of screening process, a set of vibratory parameters such as amplitude, frequency and throwing index are suggested to find out the optimum vibratory parameters for a specific screening process. The results are also used to formulate mathematical functions between the vibration parameters and the screening efficiency of the vibrating screens for different particles size.

2. DISCRETE ELEMENT METHOD (DEM)

The Discrete Element Method (DEM) is a reliable and powerful tool to study and predict the flow of particles. This methodology is being widely used in research in the area of mining, which can optimize mineral equipment design, such as ball mills, conveyors, chutes and vibrating screens (Cleary, 2010). The DEM captures the contacts between individual particles in an explicit manner. In contrast to continuum methods that smear out the individual particles into a smooth plenum, the discrete element method captures the individual geometry and dynamics of each particle, including the dissipative effects of contact friction (Dewicki, 2003).

Historically, the Discrete Element Method (DEM) had as pioneers Cundall and Strack (1979). The DEM method takes in account the translational and rotational motion equations of the particles. The mathematical model includes the interaction between particles and between particle and wall, as well as the van der Waals forces, electrostatic forces, liquid bridges, particle-fluids interaction force, etc. (Fig.1). A description of the governing equations is made by Zhou et al. (2007), as follow:
where $m_i$ and $I_i$ are, respectively, the mass and moment of inertia of particle $i$; $V_i$ and $\omega_i$ are, respectively, translational and rotational velocities of particle $i$; $F_{ij}^C$ and $M_{ij}$ are the contact force and the torque acting on particle $i$ by particle $j$ or wall; $F_{ik}^{nc}$ is the non-contact force acting on particle $i$ by particle $k$ or other sources; $F_{ij}^f$ is the particle-fluid interaction force on particle $i$ and $F_i^g$ is the gravitational force.

\begin{align}
  m_i \frac{dV_i}{dt} &= \sum_j F_{ij}^C + \sum_k F_{ik}^{nc} + F_i^f + F_i^g \\
  I_i \frac{d\omega_i}{dt} &= \sum_{j=1}^k M_{i,j}
\end{align}

where $m_i$ and $I_i$ are, respectively, the mass and moment of inertia of particle $i$; $V_i$ and $\omega_i$ are, respectively, translational and rotational velocities of particle $i$; $F_{ij}^C$ and $M_{ij}$ are the contact force and the torque acting on particle $i$ by particle $j$ or wall; $F_{ik}^{nc}$ is the non-contact force acting on particle $i$ by particle $k$ or other sources; $F_{ij}^f$ is the particle-fluid interaction force on particle $i$ and $F_i^g$ is the gravitational force.

![Figure 1. Schematic illustration of the forces acting on a particle (Zhou et al, 2007).](image-url)

### 3. DEM MODEL GENERATION

There are several commercial and non-commercial (open source) DEM software packages available. Among the commercial packages there is the EDEM from DEM Solutions, which was used in this work. The general features of this software are: general-purpose DEM simulation with CAD import of particle and machine geometry, GUI-based model set-up, extensive post-processing tools, programmable API, couples with CFD, FEA and MBD software. The software EDEM has three main components or modules: Creator (preprocessing), Simulator (solver), and Analyst (post processing). These modules are represented in Fig. 2. The details of the utilization of the modules are briefly described as follow.
3.1. Modeling using **CREATOR**

The linear motion screen was modeled for a flat screen. A 3D DEM model (Fig. 3) was set up to simulate the screening efficiency. Particulate material is iron ore, screen deck is made of rubber and screen walls are made of steel. It has been set up for the particle-to-particle contact to use the Hertz – Mindlin model (Hertz, 1882; Mindlin and Deresiewicz, 1953). For the particle-to-geometry contact it has been set to use the Hertz – Mindlin model as well. In both models no further configuration parameters are needed to be set, as the EDEM package automatically sets up the Hertz – Mindlin model for particle-to-particle and particle-to-geometry interaction.

![Figure 3. 3D Model of flat screen and collector bins for under and oversize material.](image)

All material properties are detailed in Table 1. Screen deck is a rubber square 8 x 8mm aperture hole, and 10mm thick. Screen is 260mm wide and 800mm long, which makes 208,000 mm\(^2\). Screen has a blind panel at feed and discharge ends; each measuring 260mm
wide by 100mm long, so there is a 206,000 mm$^2$ of blind area. The remaining deck area is filled by the 64mm$^2$ holes apart by 2mm in all directions on XY plane, summing up 156,000 mm$^2$ of open area, thus screen deck has a total of 53.03% of open area.

In order to create the factory plate it was created a virtual polygon centralized at the feed end of the screen. Particles are fed by gravity from a 150mm height polygon sizing 100x200mm onto the front section of screen on a blind feed panel, by a particle factory. Particles are 6.0mm diameter spherical iron ore.

Screen deck has a dynamic motion to recreate the linear motion of a vibrating screen (as shown in Fig. 4). This motion is set at the dynamic tab in EDEM. For the linear motion the sinusoidal translation is used, where it is possible to set the motion frequency, the stroke angle, which was constant at 45° for all simulations and amplitude in all three directions. Amplitude in axis Y is always zero as does not have motion in transversal direction. Displacement at axis X and Z are the projection of the amplitude in each direction, thus displacement at axis X and Z are represented by Eq. (3) e Eq.(4).

### Table 1. Material data used in simulations.

<table>
<thead>
<tr>
<th>Material</th>
<th>Poisson’s Ratio</th>
<th>Shear Modulus</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron Ore</td>
<td>0.25</td>
<td>1 MPa</td>
<td>4,250 kg/m$^3$</td>
</tr>
<tr>
<td>Rubber Deck</td>
<td>0.25</td>
<td>100 MPa</td>
<td>1,300 kg/m$^3$</td>
</tr>
<tr>
<td>Screen Wall</td>
<td>0.29</td>
<td>79.92 GPa</td>
<td>7,800 kg/m$^3$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Collisions</th>
<th>Coefficient of Restitution</th>
<th>Coefficient of Static Friction</th>
<th>Coefficient of Rolling Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore / Ore</td>
<td>0.2</td>
<td>0.6</td>
<td>0.25</td>
</tr>
<tr>
<td>Ore / Rubber</td>
<td>0.3</td>
<td>0.65</td>
<td>0.25</td>
</tr>
<tr>
<td>Ore / Steel</td>
<td>0.3</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle</th>
<th>Diameter</th>
<th>Screen Area</th>
<th>Screen Aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron Ore</td>
<td>6mm</td>
<td>208,000 mm$^2$</td>
<td>8x8mm</td>
</tr>
</tbody>
</table>

In order to generate the particles for simulation it was set a total number of 50,000 particles with a 5,000 particles per second. In order to calculate the screen efficiency it is necessary to collect all particles that pass to undersize and the particles discharged at the oversize. EDEM has a feature to create geometry like box, cylinder or polygon. The undersize

$$\text{Displacement } X = A \times \cos 45^\circ$$  \hspace{1cm} (3)

$$\text{Displacement } Z = A \times \sin 45^\circ$$  \hspace{1cm} (4)
and oversize collectors were created using the EDEM’s geometry feature. Undersize collector is a box 700x260x250mm aligned straight under the screen. To collect the particles it is necessary to disable side 1. Oversize collector is a box 200x260x150mm positioned 20mm overlapping the screen discharge end. Also to collect the oversize particles is necessary to disable side 1. In order to keep the particles over the screen deck it is also necessary to create “screen walls” at the edges. To make the screen walls it was also used the geometry box feature measuring 800x260x50mm. It is also necessary to disable sides 1, 4 and 5 to allow particles reach the screen deck and travels toward discharge end. All three boxes are made of steel. These are the necessary data and steps to create the model. Simulation could then be done.

3.2. Using SIMULATOR Module

Simulation sets are based upon the recommendation from some guidelines presented in specialized literature. In Gupta and Yan (2006) there is an information of aperture size per cut size for horizontal screens. In Chaves and Perez (2009) there is a set of recommended amplitude and frequency per cut size. Referring these authors it was decided for amplitudes and frequencies to simulate the screening process for the horizontal vibrating screen. For each pair of amplitude and frequency it is calculated the throwing index. The set of amplitude, frequency and throwing index is detailed in Table 2. Throwing index is a dimensionless parameter defined as the ratio of acceleration from vibration to acceleration from gravity i.e., 

\[ K = A \frac{\omega^2}{g} \]

as shown in Chen and Tong (2010).

<table>
<thead>
<tr>
<th>Frequency (mm)</th>
<th>Amplitude (mm)</th>
<th>Throwing Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>13,75 Hz</td>
<td>3.94</td>
<td>2.99</td>
</tr>
<tr>
<td></td>
<td>4.27</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td>4.63</td>
<td>3.50</td>
</tr>
<tr>
<td></td>
<td>4.92</td>
<td>3.74</td>
</tr>
<tr>
<td></td>
<td>5.25</td>
<td>3.99</td>
</tr>
<tr>
<td></td>
<td>6.25</td>
<td>4.75</td>
</tr>
</tbody>
</table>

Simulation time was 15s for all sets, with fixed time step of 20% of the Rayleigh Time (Dem Solutions, 2013). Data saving was set for 0.05s and a grid cell size of 4R min. The model is set up to run the simulation. In order to speed up the simulation process it is recommended to close the simulation tab pane and uncheck the Show Particles option.

3.3. Using ANALYST Module

In order to calculate the screening efficiency it was set a collector of the particles under the screen deck. These collectors are created in EDEM using the feature geometry bin. This feature allows setting up queries for counting the total number of particles within the bin. Same was done to collect the oversize particles. The screen efficiency for separation of the undersize is given by Eq.(5) as shown below:

\[ \text{Screen efficiency} = \frac{\text{number of particles within undersize bin}}{\text{total number of particles generated}} \times 100 \]
Another parameter collected in all simulations is the particle velocity on the deck. This parameter can be calculated creating a mass flow sensor over the screen deck. The Fig. 5 below shows the screen set up with all geometry bins and mass flow sensor used to characterize the screening process.

![Screen simulation arrangement with geometry bins and mass flow sensors positioned to characterize the screening process.](image)

**Figure 5.** Screen simulation arrangement with geometry bins and mass flow sensors positioned to characterize the screening process.

### 4. RESULTS AND DISCUSSION

Results from simulations are listed in Table 3. The highest efficiency obtained during simulation is 64.31%, achieved with screen amplitude at 4.75mm and frequency at 13.52Hz.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Amplitude (mm)</th>
<th>3.94</th>
<th>4.27</th>
<th>4.6</th>
<th>4.92</th>
<th>5.25</th>
<th>6.25</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Efficiency (%)</td>
<td>46.31</td>
<td>60.60</td>
<td>63.48</td>
<td>63.34</td>
<td>62.13</td>
<td>59.61</td>
</tr>
<tr>
<td><strong>Amplitude</strong></td>
<td>Frequency (Hz)</td>
<td>12.50</td>
<td>13.02</td>
<td>13.52</td>
<td>14.45</td>
<td>15.30</td>
<td>16.17</td>
</tr>
<tr>
<td>4.5 mm</td>
<td>Efficiency (%)</td>
<td>58.25</td>
<td>63.41</td>
<td>64.31</td>
<td>64.28</td>
<td>63.17</td>
<td>62.57</td>
</tr>
</tbody>
</table>

Figure 6 shows how screen efficiency varies with screen amplitude. For amplitudes lower than 4.60mm the efficiency increases when amplitude increases. After this point efficiency stays nearly flat up to the point 4.92 mm. Then an increase on amplitudes further than the 4.92 mm point shows a more aggressive reduction on the screening efficiency. The results suggest that the best amplitude for the screening this screening system is at the range of 4.6 to 4.92 mm. The relation between amplitude and efficiency can be predicted with a very low fitting error (ReLE = 0.09833) by the two term exponential equation as defined in Eq. 6. Results are ploted in Fig. 6.
Figure 6. Dependence of efficiency by amplitude.

\[ f(x) = 0.8669 \times \exp(-0.0624 \times x) - 1.27 \times 10^6 \times \exp(-3.958 \times x) \] (6)

Figure 7 shows how efficiency is affected by screen frequency. For frequencies lower than 13.52Hz the efficiency increases as the frequency goes higher. Then, at 13.70Hz frequency reaches its highest point, indicating that it is the best frequency for this specific screen system. For frequencies higher than 13.70 Hz the efficiency decreases relatively fast as frequency goes higher. The relation between frequency and efficiency can be predicted with a very low fitting error (RelE = 0.0020) by the two term exponential equation as showed in Eq. 7. The results are plotted as defined in Fig. 7.

\[ f(x) = 0.7987 \times \exp(-0.01515 \times x) - 1.292 \times 10^{12} \times \exp(-2.435 \times x) \] (7)

Figure 8 shows how the efficiency changes with the throwing index. It is clear that the throwing index between 3.2 and 3.5 are at the highest points for this screen process. For throwing index lower than 3.2 there is a rapidly growth in the screen efficiency as the
throwing index increases. For throwing index higher than 3.5 the screen efficiency reduces very slowly as the throwing index gets higher. The relation between the throwing index and the screen efficiency can be predicted by a two terms exponential equation as per Eq. 8, as shown in Fig. 8. The relative fitting error is very low with 0.0151.

\[ f(x) = 0.704 \times \exp(-0.02895 \times x) - 1.179 \times 10^{12} \times \exp(-10.17 \times x) \quad (8) \]

5. CONCLUDING REMARKS

This paper has established the basic steps to create a simulation model to characterize the horizontal screening process through Discrete Element Method using EDEM 3D Simulation. The results from the simulations correlate with other published papers and specialized literature about Discrete Element Method and Mineral Screening.

The secondary purpose to find out a relationship between screening efficiency and vibration parameters including amplitude, frequency and throwing index based on EDEM 3D simulation was reached for this basic screen process. However, industrial screening varies more than the model created. The following steps of this research are to recreate a model closer to the industrial screening process.

The influence of the vibration parameters could be fitted so the optimized set of parameters to reach the highest screen efficiency could be found.

The best set of vibration parameters was amplitude of 4.70mm, frequency of 13.75Hz and throwing index of 3.55G. This set gave the efficiency of 64.33%.

Throwing index it is a major factor in the screen design, as it is close related to screen dynamic load. Thus, 3D EDEM simulation may be used to determine the lowest throwing index that will not affect strongly the screen efficiency. It is valuable information for screen designers.
In a similar approach other parameters can be simulated to understand its influence over the efficiency. Influence of parameters such as open area, deck material, particle size/aperture ratio, screen inclination and screen length may also be established.

REFERENCES


