Minerals Engineering 119 (2018) 191–204

Contents lists available at ScienceDirect

Minerals Engineering

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

Effect of particle cohesion on flow and separation in industrial vibrating screens

Paul W. Cleary*, Padarn Wilson, Matt D. Sinnott

CSIRO Data61, Private Bag 10, Clayton South 3168, Australia

ARTICLE INFO

Keywords:
DEM
Screen
Cohesion
Separation
Percolation

ABSTRACT

Screens are often used to separate large volumes of granular materials according to size. Discrete Element Method (DEM) modelling using non-spherical particle representations has previously provided increased understanding of the operation of such industrial screens operating both wet and dry. If a granular material has any combination of moderate amounts of water or clay present then it can become sticky which then affects its flow properties. We examine the influence of inter-particle cohesion on flow through and separation efficiency of such screens using a DEM model that includes a simple representation of the cohesive force. For high levels of cohesion the stickiness of the bulk material prevents proper flow through the machine with material building up in the rock box and then overflowing its back. For intermediate cohesion levels the material behaviour changes rapidly from sticky and difficult to flow to one for which particles can be properly processed by the screen. For lower cohesion levels the screen separation performance becomes independent of the level of cohesion level and behaves as if the material is cohesionless.

1. Introduction

Banana and straight screens are often used for high capacity separation of iron ore, coal, aggregates and other bulk materials into different size fractions (Naper-Munn et al., 1996). The screens can have one or multiple decks if more than one product size is required. Banana screens have curved decks with higher slopes at the feed end progressing to shallower at the discharge end ((Naper-Munn et al., 1996). Straight screens have the same orientation of the deck at all points along the screen length. Each deck is fitted with a series of screen panels each with arrays of square, rectangular, chevron or other shaped holes. These can be varied between decks and along decks as long as good information is available to inform the choices at each location.

The screen structure is vibrated at high frequency to generate peak acceleration in excess of gravity, typically 4–6 times gravity, in order to agitate the bed and drive percolation of finer particles down through the shearing bed and to then pass through the screen panels. A dense stream of particles is loaded onto the upper end of the screen. They accelerate down along the steep early panels of the banana screen and then slow as the panel angle decreases towards the discharge end. The steeper angle at the feed end of the screen is intended to help provide rapid initial acceleration of the bed down the screen. Material discharging from the end of the top of the deck is normally regarded as oversize and may be either a coarse product or can be sent back to be re-crushed and returned to the screen. Smaller particles pass through the top deck panels to form a flowing bed on the lower deck whose particles undergo further size sorting to create a middle product stream from the end of the bottom deck and an underflow stream of finer material that passes through the lower deck.

Measurement and sampling is difficult on top decks of screens and even more difficult from lower decks which are also difficult to visually observe. These difficulties in obtaining actionable experimental data make design and optimisation of screens challenging. Mathematical modelling has been used to provide some understanding of the screening process. Early models presented for batch screening by Standish (1985) and continuous screening by Standish and Meta (1985) and Standish et al. (1986) were based on reaction kinetic and probability theories. The major limitations of these approaches are that they only consider the path of a single particle and do not account for interactions with other particles.

Semi-mechanistic phenomenological models for a simple linear vibrating screen were developed by Soldinger (1999). These assume screening consists of two processes: stratification of material through the vibrated bed; and passage of material from the bottom layer of the bed through the screen apertures. Such models rely on fitting empirically determined parameters. Soldinger (2000) later extended this model to include material loading effects and the screening efficiency of different sized particles. In comparison with real screening data, these

---

* Corresponding author.
E-mail address: Paul.Cleary@csiro.au (P.W. Cleary).

https://doi.org/10.1016/j.mineng.2018.01.037
Received 5 December 2017; Accepted 29 January 2018

models significantly underestimate the mass flow rate of product through the first half of the screen length. More recently, Asbjörnsson et al. (2016) used this approach to model the screening efficiency of a double deck banana screen. Their simulation results predicted a much finer product through the top deck of the screen. The limitation of these models for more complex screening applications is that they only solve for mass flow. They do not account for the effects of granular collisions within the bed and with the screen surface which can significantly delay passage of material via crowding of screen apertures as well as influence the local varying porosity of the vibrated bed which will constrain stratification rates. They also particularly do not include dependences on particle shape or the presence of water.

The Discrete Element Method (DEM) allows systems to be modelled at the particle level and includes interactions both between particles and between particles and the screen. The force distribution under granular beds is complex (Liffman et al., 2001) and for a screen influences the rate of flow through the screen at each point. DEM is able to capture such bed pressure effects, influences of the shear flow structure within the bed, the nature of the resultant percolation induced size segregation that occurs within the bed and finally the detailed dynamics of how particles move through the holes in the screen deck. The earliest DEM modelling of a screen was by Cleary and Sawley (2002) and then Cleary (2004) who considered a three-dimensional model of a periodic section of a flat inclined screen deck using spherical particles. Cleary (2009) used a comparison of the separation performance obtained using spherical and non-spherical particles on the same screen to demonstrate the critical importance of including the particle shape in the DEM model.

Dong et al. (2007) and Li et al. (2003) performed DEM modelling of non-periodic screens but these were limited to two dimensions and small numbers of particles which were circular and which included only limited size variation. Cleary et al. (2009a,b) performed an extensive 3D DEM analysis of the performance of a full industrial-scale iron ore scalping double deck banana screen. The super-quadric particle shape approach was shown to be a good representation of the particles. The model included the full double deck screen (frame and cloth panels), the feeder and the collecting chutes and conveyors. This enabled detailed analysis of transport and separation on each deck and the identification of the contributions of each panel, power consumption, particle degradation and screen wear for a range of peak accelerations.

Dong et al. (2009) also used DEM to evaluate the influence of deck vibration and particle speed on separation of spherical particles using a highly simplified periodic slice of a single deck banana screen. Dong et al. (2013) then compared this model under similar operating conditions to the measurements of Standish and Meta (1985). They obtained good agreement for screened masses for the latter half of the screen length but their model overestimated the partition number for near grate sized particles.

Delaney et al. (2012) performed detailed validation of DEM screening predictions when spherical particles were used to represent the particles. This showed unequivocally that DEM using particles approximated as spheres significantly over-predicts the separation efficiency of near grate sized particles and massively over-predicts pegging of screen holes leading to non-steady and incorrect predictions of separation performance. Elskamp and Kruggel-Emden (2015) benchmarked their DEM simulation for a square periodic section of linear vibrating screen against other batch screening phenomenological process models in the literature for different particle-scale details and screen operating conditions. Jahani et al. (2015) developed DEM models using the industrial-scale double-deck banana screen geometries from Cleary et al. (2009a,b) and the lab-scale single-deck geometries from Dong et al. (2009) and studied the effect of panel inclination and screen operating conditions in terms of screening efficiency and recovery. They compared their lab-scale geometry results against Dong et al. (2009) and found good agreement, but no comparison was made against the model of Cleary et al. (2009a,b).

Fernandez et al. (2011) considered the flow of slurry through the granular beds during wet separation on the same double deck banana screen as used in Cleary et al. (2009a,b). The slurry prediction used the 1-way coupled DEM-SPH approach introduced by Cleary et al. (2006). This has also been used for slurry flow prediction in tower mills (Sinnott et al., 2011) and SAG mills (Cleary and Morrison, 2012). The slurry velocity distribution throughout the screen was found to closely match that of the particulates due to the strong controlling effect on the slurry of the inter-phase drag. It was also found to be insensitive to the viscosity. Conversely, the slurry volume fraction distribution varied strongly throughout the screen and could be very different to the distribution of the particulates.

Many bulk materials to be separated can be damp (with moisture levels between 0 and 10% by volume) which is enough to make interstitial finer particles or attached clay materials sticky. These moisture levels, however, are sufficiently low that the moisture is not able to move independently of the granular material (and so cannot reasonably be characterised as a slurry) and so the use of multiphase DEM-fluid models (such as the one used by Fernandez et al., 2011) are not appropriate. Such stickiness can be included in a DEM model directly using an explicit cohesion model. Cleary and Robinson (2011) proposed such a cohesion model which was suitable for modelling large scale bulk materials in the context of particle sampling. This model was able to reproduce the fragmentation of the stream of cohesive material from the head pulley of a conveyor belt. It also showed that the presence of cohesion caused agglomeration of particles and inhibited the mobility of smaller particles within dense granular materials with wide size ranges. This was found to be positive for minimising the generation of sample bias. Mabote (2016) developed a phenomenological process model for wet fine screening applications using pilot data for varying feed rates, grate size and solids content. This was extended to handle multi-component ores and changes in operating conditions using the 2-parameter Whiten screen model. Higher solids concentrations (more cohesive material due to reduced water phase) were found to give worse screening performance.

In the context of screening, the restriction of fine scale particle mobility (due to their being stuck to larger nearby particles) can potentially have adverse impacts on the percolation mechanism responsible for finer particles settling through the shearing beds found on vibrating screens. Countering this is the presence of strong collisional and shear forces due to both the bed shear and the vibrational motion of the screen that can potentially break cohesive bonds between the particles that may inhibit mobility. Neither effect is understood in isolation nor is their combined effect understood. It is therefore important to explore these issues and to establish how the level of cohesion influences the overall process separation behaviour for industrial screens. In this paper, we extend our previous DEM screen model further to include the effects of inter-particle cohesion and explore their impact on the material flows within the screen and on the separation efficiency produced.

2. Simulation Methods

2.1. The DEM method for predicting particle flow

DEM is a well-established numerical method which has been used extensively to study the granular flow of material. It simulates such flows by tracking individual particles and predicting their interactions between one another and boundary objects (such as the screen deck, feeder, chutes and outgoing conveying belts used in this paper), using a contact law to predict instantaneous positions, orientations, velocities and spins of the particles. The DEM code used in this study has been reported on extensively (see Cleary, 1998, 2004, 2009 for details and examples). A linear-spring dashpot model is used. Particles are allowed to overlap and the amount of overlap Δx, and normal v_n and tangential v_t relative velocities determine the collisional forces via a contact force