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Prediction of slurry transport in SAG mills using SPH fluid flow in a dynamic DEM based porous media

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Abstract

DEM modelling of the motion of coarse fractions of the charge inside SAG mills has now been well established for more than a decade. In these models the effect of slurry has broadly been ignored due to its complexity. Smoothed particle hydrodynamics (SPH) provides a particle based method for modelling complex free surface fluid flows and is well suited to modelling fluid flow in mills. Previous modelling has demonstrated the powerful ability of SPH to capture dynamic fluid flow effects such as lifters crashing into slurry pools, fluid draining from lifters, flow through grates and pulp lifter discharge. However, all these examples were limited by the ability to model only the slurry in the mill without the charge.

In this paper, we represent the charge as a dynamic porous media through which the SPH fluid is then able to flow. The porous media properties (specifically the spatial distribution of porosity and velocity) are predicted by time averaging the mill charge predicted using a large scale DEM model. This allows prediction of transient and steady state slurry distributions in the mill and allows its variation with operating parameters, slurry viscosity and slurry volume, to be explored.

Keywords: Comminution; SAG milling; Discrete element modelling; Computational fluid dynamics

1. Introduction

Even though the first commercially successful autogenous mills were operated dry, almost all autogenous (AG) and semi-autogenous (SAG) mills in use today are operated with water and ore fed to the mill in a more or less fixed ratio. The water forms a slurry with fine ore particles. This slurry is much more efficient than air at transporting ore progeny and finished product (sufficiently comminuted particles) out of the mill. As overly fine particles (“slimes”) are usually more difficult to separate, fine progeny should be removed from the mill as soon as possible after generation. The removal process has been the subject of considerable controversy in recent years as inadequate slurry removal capacity can constrain mill throughput (Royston, 2000; Warder and Davies, 1994). However, if the charge is not kept well laden with slurry, the mill capacity to produce fine particles will be reduced as fewer collisions between large particles will interact with the layer of slurry between them. Hence, there is substantial incentive to better understand (and to model) both the hold up and flow through mechanisms within the charge as well as the pulp removal capability of the classifying grates and pulp lifters.

There are some other operational issues which may usefully be addressed:

- *Flow back:* Both scale modelling and pulp lifter wear patterns strongly suggest that a high proportion of the slurry which flows through the grates into the pulp lifter chamber while they are in contact with the charge simply flows back into the mill once the pulp lifters have risen above the free surface of the charge. and passes

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the highest point in its rotation (top dead centre). The pulp and pebbles on the lifters may also fall at close to vertical onto the next pulp lifter and cause rapid wear on the lifter "backs". This was clearly demonstrated using DEM simulation of a pilot scale mill by Cleary (2004). A pulp lifter designed to act as a one way valve (Nicoli et al., 2001) has substantially improved the operation of some high slurry load mills and curved pulp lifters have also improved pebble discharge (Royston, 2000). In both cases, mill rotation is limited to one direction. This limits maximum liner and pulp lifter life compared with reversible mills.

- *Slurry pooling:* With inadequate pulp lifter capacity, a pool of slurry may form at the toe of the charge. If this pool rises into the impact zone, it can restrict impact breakage and cause rapid mill charge overload. As noted earlier, a small degree of pooling probably maximises fine grinding.
- *Charge "lubrication":* The cascade of charge within the mill absorbs most of the energy and probably does most of the grinding. If the charge becomes overly full of slurry, there may not be enough frictional energy transferred to it. In this scenario, the mill charge slumps, grinding stops and rapid mill overload results.

2. Approach to simulation

The problem of slurry transport in mills requires both the ability to model the particulate solids and the slurry. The most suitable method for modelling the coarse particulates in the charge is the discrete element method (DEM), see Cleary (1998a, 2001a,b,c, 2004) and Cleary et al. (2004) for details. Smoothed particle hydrodynamics (SPH) is a powerful method for modelling complex, splashing, free surface fluid flows, (see Cleary, 1998b; Cleary et al., 2006a; Cleary and Prakash, 2004 for details) and this will be used for modelling the slurry. The methodology proposed here to explore the flow of slurry in mills uses a sequential DEM–SPH model. The process has three key steps:

- Perform a DEM simulation to predict the particle flow and average the particle data onto a cylindrical grid to obtain steady state volume fraction and velocity distributions that then well characterise the charge.
- Supply the continuum porosity and velocity information from the DEM simulation to the SPH code. The mill geometry used by the two codes is the same but the charge representation changes from discrete to continuous.
- Perform an SPH simulation of the distribution of slurry in this charge using a supplied slurry viscosity and a Darcy law porous media drag based upon the porosity and velocity distributions within the charge.

This sequential model is possible because the particulate flow is in steady state and the coarse particulates represented in the DEM are only weakly affected by the slurry motion. The slurry motion through the charge is dominated by the flow of the particulates in the charge. Therefore this one way coupling is able to capture the majority of key physics required to predict slurry behaviour. It allows prediction of slurry distribution within the mill (both in the radial and axial directions) as well as axial transport, including discharge through the grates and flow in the pulp lifters and on the discharge cone. Inclusion of the weak coupling of the slurry back onto the coarse particulates will require a fully coupled SPH–DEM model which will be the subject of future work.

This porous media approach allows us to consider slurry pooling and slurry flow into pulp lifters without the computational expense of a fully coupled model. The pulp lifter model requires only an SPH slurry model unless pebble ports are also required. This is a new approach for including the effects of the charge in the prediction of the fluid motion. In order to demonstrate the concept the modelling will be performed only in two dimensions. However, the approach is easily generalised to three dimensions.

3. Computational methods

Here we will briefly describe both the DEM and SPH methods and the additions required for the SPH method to include the Darcy porous media drag.

3.1. DEM modelling for the particulate solids

DEM simulation involves following the motion of every particle in the flow and modelling each collision between the particles and between the particles and their environment (such as the mill liner). The particles used here will be circular with a broad and realistic size distribution. The general DEM methodology and its variants are well established and are described in review articles by Barker (1994), Campbell (1990) and Walton (1994). The specific DEM implementation used here is described in Cleary (1998a, 2001a,b, 2004). Briefly, the 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 law. We use a linear spring-dashpot model in which the normal force is:

$$F_n = -k_n \Delta x + C_n v_n. \quad (1)$$

This consists of a linear spring to provide the repulsive force and a dashpot to dissipate a proportion of the relative kinetic energy. The maximum overlap between particles is determined by the stiffness k_n of the spring in the normal direction. Typically, average overlaps of 0.1–0.5% are desirable, requiring spring constants of the order of 10^7 N/m in two dimensions. The normal damping coefficient C_n is chosen to give the required coefficient of restitution ε (defined as the ratio of the post-collisional to pre-collisional normal component of the relative velocity).