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Analysis of cone crusher performance with changes in material properties and operating conditions using DEM

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ABSTRACT

Discrete Element Method (DEM) simulation with non-round particles and including breakage has been used to understand the breakage behaviour and operating performance of an industrial scale cone crusher using a representative ore. The breakage model uses a replacement strategy and impact energy specific progeny size data from a Drop Weight Test (DWT). There is a strong variation in the breakage behaviour with height in the compression region as the differing profiles of the concave and mantle create five different regions with monotonically decreasing width and differing degrees of convergence between the surfaces. These control the rate of motion and the ability to load and break the particles, and determine whether high forces are generated via multi-particle stress chains or as single particle loading directly from the liner surfaces. The larger feed particles jam in the compression zone prior to breakage and cause observable obstruction to the flow of finer material and strong non-uniformity in the flow of product down the lower part of the mantle. Trends in the coarseness of product and changes in steady state throughput are identified with changes in material properties (rock breakage energy and friction coefficient) and crusher operating parameters (Closed Side Setting and crusher rotation rate).

1. Introduction

Comminution involves the reduction in size of particulate materials such as bulk commodities and ore. Large feed particles are fractured making material that is increasingly fine. Breakage of larger sizes is typically termed crushing whilst breakage of smaller feed is usually termed grinding. A cone crusher is a device that breaks rocks by squeezing them between an eccentrically gyrating cone (also called a mantle) and a concave (Napier-Munn et al., 1996). The mantle and the concave both have wear resistant liners attached that gradually erode and change shape. Particles enter the cone crusher from the top then travel down until they are near the working surfaces where they become trapped between the mantle and the concave and have the potential to be broken multiple times by the large compressive forces applied. Larger rocks are broken first with their progeny falling to lower positions in the crusher where they are typically broken again until they are sufficiently small to exit from the bottom of the crusher. The output of a cone crusher is controlled by the Closed Side Setting (CSS) which is the minimum approach of the mantle and concave at any height. This determines the peak strain that can be applied to a particle of a specific size and therefore whether it will break and into what fragments. The Open Side Setting (OSS) on the opposite side to the CSS is the maximum constricted separation of the mantle and concave and essentially controls the vertical flow of material as the gap opens and particles become mobile and move downwards (Andersen and Napier-Munn, 1990; Napier-Munn et al., 1996, Chapter 6).

The performance of a cone crusher is dependent on the shape of the concave and mantle, both of which wear as a result of the breakage. The mantle is moved incrementally upward as the liner wears in order to maintain the CSS. Typically design, optimisation and customisation of crushers have been performed using experimental approaches. This can be as simple as spot measurements of the liner through to full laser scanning of the liner surface during shut-downs (Franke et al., 2012; Rosario et al., 2004). Crusher wear has also been correlated with crusher operating conditions for real-time optimisation of performance (Hulthén, 2010). Measurement of liner wear during operation and direct observation and measurement of breakage are not possible for real operating crushers. This lack of detailed data has limited the progress in understanding and optimising such crushers.

Discrete Element Modelling (DEM) is a computational technique that allows particle flows in various types of equipment to

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be simulated providing detailed information on what is happening in the machine, both at the individual particle scale and as an overall process. It has been used extensively in the simulation of tumbling mills (see review by Weerasekara et al., 2013) but has been rarely used in modelling of crushers. Simulation of crushing machines is much less common in the literature. This is in part due to the increased complexity of such a simulation due to a combination of the:

- Requirement to include the breakage directly in the simulations in order to allow the particles to transit through the equipment,
- Inclusion of particle shape (Kojovic, 1994),
- Larger model sizes (in terms of numbers of particles in the crushers), and
- High level of geometric complexity of the crushers.

Particularly in compression based crushers, which all use a process based on squeezing particles in a progressively narrowing space between opposing surfaces, the DEM particles are unable to physically pass through the machine unless the model actually breaks them into smaller particles. Since most DEM software does not include such capabilities, there is correspondingly less simulation of crushers compared to mills.

Three different approaches have been used to date for representing breakage in DEM:

1. Using bonded clusters of particles which are typically circular or spherical,
2. Bonded polyhedral sub-particles,
3. Using a replacement strategy where a breaking parent is replaced by an assembly of progeny packed into the parent particle volume.

The bonded DEM approach has been used by Thornton (1996), Thornton et al. (1999), Kafui and Thornton (2000), Tomas et al. (1999) and Schubert et al. (2005) to explore breakage of small cohesively bonded powders and for concrete agglomerates. It has also been used extensively in geomechanical applications, particularly with Particle Flow Code (PFC) in both two and three dimensions (Potyondy and Cundall, 2004; Jiang et al., 2011; Schöpfer and Childs, 2013). Characterisation of the breakage properties of rocks for milling or crushing has also been examined (Refahi et al., 2007; Whittles et al., 2006). The study of rail ballast behaviour and degradation under cyclic loading from passing trains has been performed using bonded particle DEM. PFC2D with simple breakage models was used by Hossain et al. (2007), Indraratna et al. (2009), Thakur et al. (2010). PFC3D was used by Lu and McDowell (2010) for comparable studies in three dimensions. Lobo-Guerrero and Vallejo (2006) explored the effect of cyclic loading on rock ballast along the center of a rail line using a two dimensional model with a breakage method that is similar to the one used here. All these models were small in terms of numbers of particles and very simple in their geometric configurations.

The second approach for simulating the detailed fracture of a non-agglomerate particle was proposed by Potapov and Campbell (1994, 1996). They represented the particle as an assembly of bonded rigid or deforming tetrahedral elements. This produced realistic results but at a high relative computational cost. Recently, Eliáš (2014) used a similar bonded polyhedral model for fracture of small numbers of non-round particles in a compression test. This used a highly simplified progeny model with each fracturing particle breaking into four relatively similar sized daughter particles.

The third approach was introduced for comminution by Cleary (2001a). In the replacement strategy, particles to break are identified on the basis of either their energy absorption (for impact breakage) or from high stresses (for compression breakage). This approach was used for modelling a grinding table (Cleary et al., 2008) and for breakage in a pilot mill (Delaney et al., 2013).

DEM simulation of lab-scale cone crushers has been reported by Herbst and Potapov (2004) and Quist and Evertsson (2010). Single particle breakage in jaw crushers has been modelled using DEM by Legendre and Zevenhoven (2014) and Refahi et al. (2010) using bonded particle models. Lichter et al. (2009) replaced the bonded polyhedral cluster approach of Herbst and Potapov (2004) with a replacement style model which used polygonal elements and a micro-scale Population Balance Model (PBM) to specify the progeny following a fracture event. This was applied to a continuous lab-scale cone crusher and gave realistic predictions but at a computational cost that prevented its use on a full-scale crusher.

The replacement model of Cleary (2001a) with spherical particles has recently been used by Cleary and Sinnott (2015) and Sinnott and Cleary (2015) for investigating several classes of full scale industrial compression and impact crushers respectively. Recently, Delaney et al. (2015) introduced a more sophisticated version of this model in which the DEM particles, represented as super-quadric shapes, broke into non-round progeny whose size distribution was determined by empirical data based on DWT (Drop Weight Test) data formulated in the form of a JKMRC t_{10} breakage model. This model was demonstrated on an industrial scale cone crusher with a narrow coarse feed material and gave realistic predictions for particle flow and breakage locations within the crusher. The packing of the progeny in this breakage model is based on a methodology given in Delaney and Cleary (2010a) and Delaney et al. (2010b).

In this paper, we use the DEM model presented by Delaney et al. (2015) based on compression breakage of non-round particles and the replacement breakage method using progeny generated from t_{10} characterisation of breakage to explore the dependence of the machine performance with variations in operating conditions and material properties for a full size industrial cone crusher. In this work the material properties will be assumed to be size independent.

2. Numerical method

2.1. The DEM model

The DEM method is now well known so the method will not be explained in detail. The specific implementation used here has been developed in-house by CSIRO and has been extensively applied for the study of comminution (Cleary, 1998a, 1998b, 2001a, 2001b, 2001c, 2009a, 2009b; Morrison and Cleary, 2004, 2008; Cleary et al., 2008; Sinnott et al., 2006, 2011). The contact model used is a linear spring-dashpot. Details are contained in the earlier references and in Thornton et al. (2013) who provide a comparison of the behaviour of most currently known inelastic contact models. The particles are non-round (which is critical for the reasonable representation of real rock particles) and are represented as super-quadrics (see Cleary and Sawley, 2002 and Cleary, 2004 for details).

Particle shape is critical to flow behaviour, yield stress, failure, porosity and permeability (see Cleary, 2009a for a description of the issues relating to shape in granular flows). This needs to be accounted for in the geometric representation of the particles. Throughout this paper (except for the rounded particles and media in the mill applications where the particles are actually close to spherical) the particles are represented as super-quadrics. This shape is given in their principle reference frame as:

$$\left(\frac{x}{a}\right)^m + \left(\frac{y}{b}\right)^m + \left(\frac{z}{c}\right)^m = 1 \quad (1)$$