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Discrete Element Modelling of Rock Communition in a Cone Crusher using a Bonded Particle Model

Authors: Huiqi Li, Faculty of Engineering, University of Nottingham;

Glenn McDowell, Faculty of Engineering, University of Nottingham;

Ian Lowndes, Faculty of Engineering, University of Nottingham.

Abstract

It is known that discrete element method modelling (DEM) of rock size reduction can be achieved by two approaches: the population balance model (PBM) and the bonded particle model (BPM). However, only PBM has been successfully used in DEM modelling cone crusher in the literature. The aim of this paper is to explore the feasibility of using the BPM to represent the size reduction of rock experienced within the cone crusher chamber. The feed rock particles were represented by isotropic dense random packing agglomerates. The simulation results were compared with the PBM simulation results, and it was shown that the BPM cone crusher model was able to satisfactorily replicate the performance of a cone crusher as well and it can provide more accurate prediction of the percentage of the fine products. In addition, the novel contribution here is that the rock feed material comprises particles of realistic shapes which break into more realistically shaped fragments compared with the fragments with defined shapes in the PBM model.

Introduction

The cone crushers is the most common type of mineral comminution machine that is used widely in the minerals and aggregates extractive industries to crush medium or above medium sized rocks. The use of an incremental build and the testing of alternative design prototypes is expensive, often requiring the production and several models to identify the required an economic improvement in the crusher performance. The development of a validated computational simulation mode of a cone crusher could significantly reduce the required lead time and costs. The discrete element method (DEM) (Cundall and Strack, 1979) provides a potential method to investigate the mechanical behaviour of the flow and breakage of granular material on both the micro and macro scales. The PBM approach replaces the predicted failed parent particle by a number of new and smaller fragments while the BPM approach represents individual particles as an assembly of bonded micro-spheres, with breakage simulated by the failure of some of the bonds. The Population Balance Model (PBM) (Herbst et al, 2003) has already successfully been applied in DEM modelling cone crusher performance (Lichter et al, 2009; Li et al, 2014). However, as the progeny fragments have to be formed and located at the position of the parent particle, the PBM approach cannot replicate the movement of the original parent and the subsequent progeny particles formed post failure. In contrast, BPM can consider the particle movement as a result of a crushing sequence as the agglomerate is directly broken into smaller particles. The research results presented in this paper explore the feasibility of the use of BPM to simulate the performance of a cone crusher using DEM, the feed rock particles are represented by a collection of dense randomly packed agglomerates of bonded micro-spheres, and the simulation results will be compared with the PBM simulation results provided by Li et al (2014).

The construction of DEM cone crusher model

The program PFC3D (Itasca, 2008) and the prototype cone crusher constructed by Li et al (2014) were used in this study. Figure 1and Figure 2 illustrate typical vertical and horizontal cross-sectional views through a cone crusher. Table 1 shows the scale of the prototype cone crusher and the corresponding parameters are illustrated in Fig 1. The reader is referred to the work of Li et al (2014) for the details of the geometry of the cone crusher. Figure 3 shows an illustration of the representative 3D rendered surfaces of the mantle and concaves formed within a typical DEM cone crusher model.

Table 1. Parameter values used to construct the DEM cone crusher model

F(mm)	CSS(mm)	s(mm)	$\beta(^\circ)$	$\alpha(^\circ)$	$\gamma(^\circ)$	ΔL(mm)	D_c(mm)
55	12-18	4.5	18-22	45	2	50	300

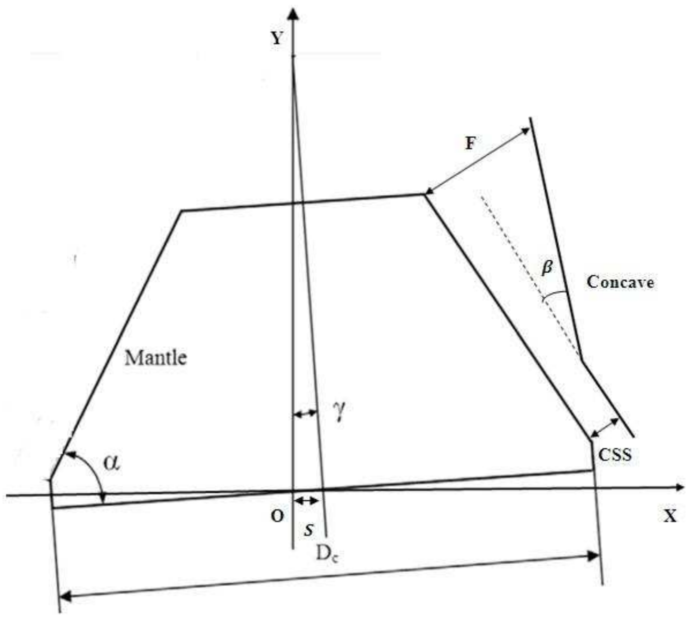

Figure 1. A vertical cross-section view through a typical cone crusher.

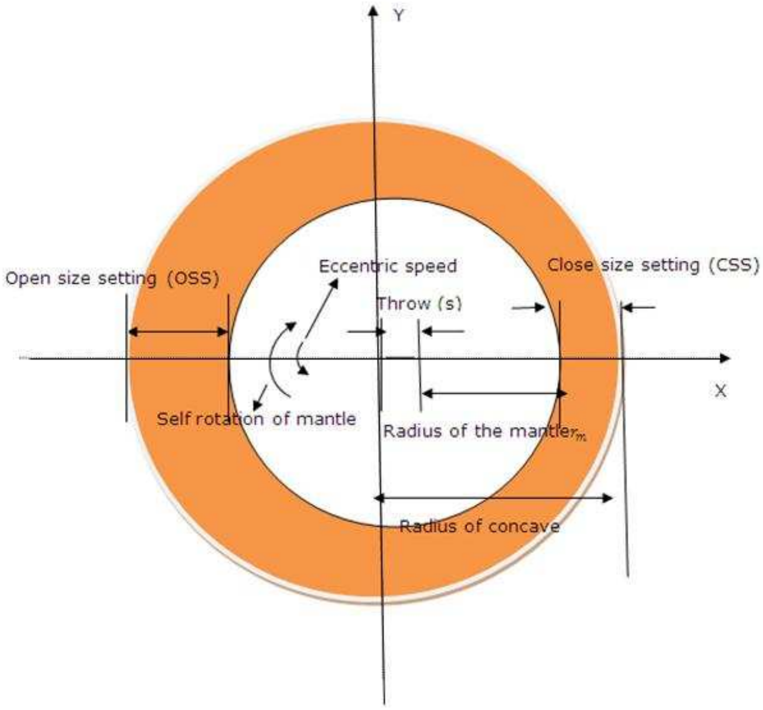

Figure 2. A horizontal cross-section view through a typical cone crusher

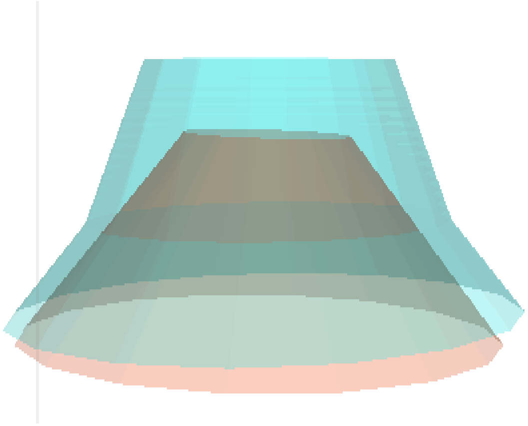

Figure 3The DEM cone crusher model

Agglomerate calibration

Various types of agglomerates has been used for DEM modelling of particle breakage: hexagonal closed packing agglomerate (Cheng et al, 2003; Lim, 2004; Lim and McDowell, 2007), agglomerates generated by the radius expansion method (Cil and Alshibli, 2012; Potyondy & Cundall, 2004) and dense random packing agglomerates (Li et al, 2013). As a dense and isotropic particle is desired, the dense random agglomerate generated by Li et al (2013) was used in this study which is achieved by inserting particles to fill the voids in the agglomerate. The generation detail is given in detail by Li et al (2013).

Li et al (2014) diametrically crushed granite ballast particles of three sieve size fractions and found that for each size fraction the tensile strengths of 30 particles followed the Weibull distribution (Weibull, 1951). The tensile strengths were then used as the breakage criterion their PBM modelling of the cone crusher performance. In order to compare with Li et al (2014)'s PBM simulation results, the agglomerates are calibrated to have same tensile strengths distribution with granite ballast particles crushed in Li et al (2014)'s diametrical compression tests. The spherical dense random packing agglomerate used here is an isotropic particle (Li et al, 2013); in this case it is expected that the strength of the agglomerate is proportional to the bond strength (Cil et al, 2013; Li, 2013).Thus, the modelling of the variation of particle strengths can be achieved by simply giving each agglomerate a single value of bond strength which is taken from the relevant distribution of the experimental results. The calibration process is as following：

- The Young"s modulus was chosen with a Poisson ratio of 0.2, to give an initial elastic response which matched the experiments.
- The agglomerate was given a random bond strength, assuming a Weibull modulus equal to that for the Weibull distribution of particle strengths in the experiments.

- This agglomerate was then crushed to obtain its strength σ.
- The bond strength was then scaled by ($\frac{\sigma}{\sigma_o}$) to obtain the assumed 37% bond strength Bo.
- The agglomerates were then assumed to have a bond strength given by a Weibull distribution with the chosen m and a 37% bond strength Bo.

McDowell and Li showed in the discussion Cil et al (2013) that the crushed agglomerates had approximately the same distribution of strengths as the assumed bond strength distribution, if the average bond strength is scaled to give the correct average agglomerate strength, and the reader is referred to Figure 6 of that discussion. The calibrated micro input parameters were shown in Table 2. Further explanations of the definitions of the parameters are given by Itasca (2008).

Table 2 Input values of micro parameters of the agglomerate used in BPM DEM cone crusher model

Parameter	values
micro-ball radius	0.0025m
micro-ball density	2700 kg/m^3
friction coefficient	0.5
Young's Modulus	70GPa
Poisson's ratio	0.2
parallel bond radius multiplier	1
parallel bond normal stiffness	5*10^{12} N/m
parallel bond shear stiffness	2*10^{12} N/m
37% normal/shear bond strength, Bo	60MPa

Simulation procedure

The DEM simulation models used 100 particles as the feed material. The sizes of the particles were chosen to be in the range 14-28mm, which is smallest size fraction of the ballast particles crushed experimentally (to save computational time).The number of spheres in each agglomerate ranges from 1,328 to 1,512 and the total number of the spheres forming the 100 particles is 141,368.The particle shape was also considered and this is a unique feature of the approach presented in this paper. Figure 4 details the modelling stages used to generate the irregular agglomerate shapes.

- Generate a spherical random dense packing agglomerate of radius ratio 4 (the ratio of the radii of the largest and smallest spheres in the agglomerate); a radius ratio of 4 is lowest ratio required to generate a dense isotropic particle using the filling void method proposed by Li et al (2013). The radius of the agglomerate should be at least equal to the measured sieve size of the real particle.

- Calculate the three dimensional external profile of the real particle. The tool used here was a 3D laser digitizer.
- Check the centres of all the spheres in the agglomerate to reject the spheres whose centres lie outside the boundary.

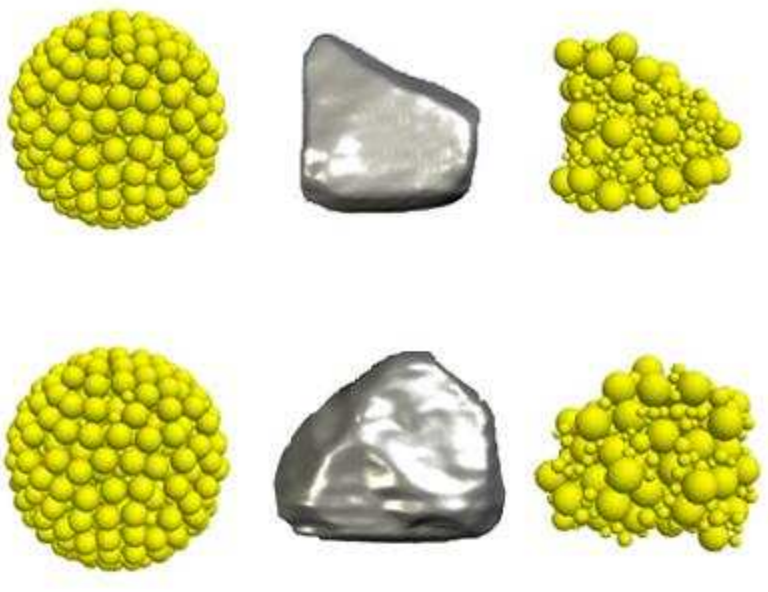

Figure 4The modelling procedure used to generate irregular particle shapes

The simulation procedure was shown in Figure 5, which depicts animation stills of the sequential stages of the solution of the model. The procedure is as follows:

- 100 particles of radius 28mm were randomly generated inside the artificial cylinder wall above the mantle - see Figure 5(a).
- The spheres are replaced by agglomerates - see Figure 5(b).
- The agglomerates are deposited into the feed bin by gravity. The bonds of the agglomerates are given an artificially high bond strength to avoid breakage during the deposition process. A flat artificial wall is constructed above the concave to avoid the particles dropping into the chamber directly- see Figure 5(c).
- The bonds in the agglomerates are re-allocated their normal values. The flat artificial wall is then deleted to allow the particles to flow into the chamber - see Figure 5(d).

- The mantle is rotated– see Figure 5(d)-(e).

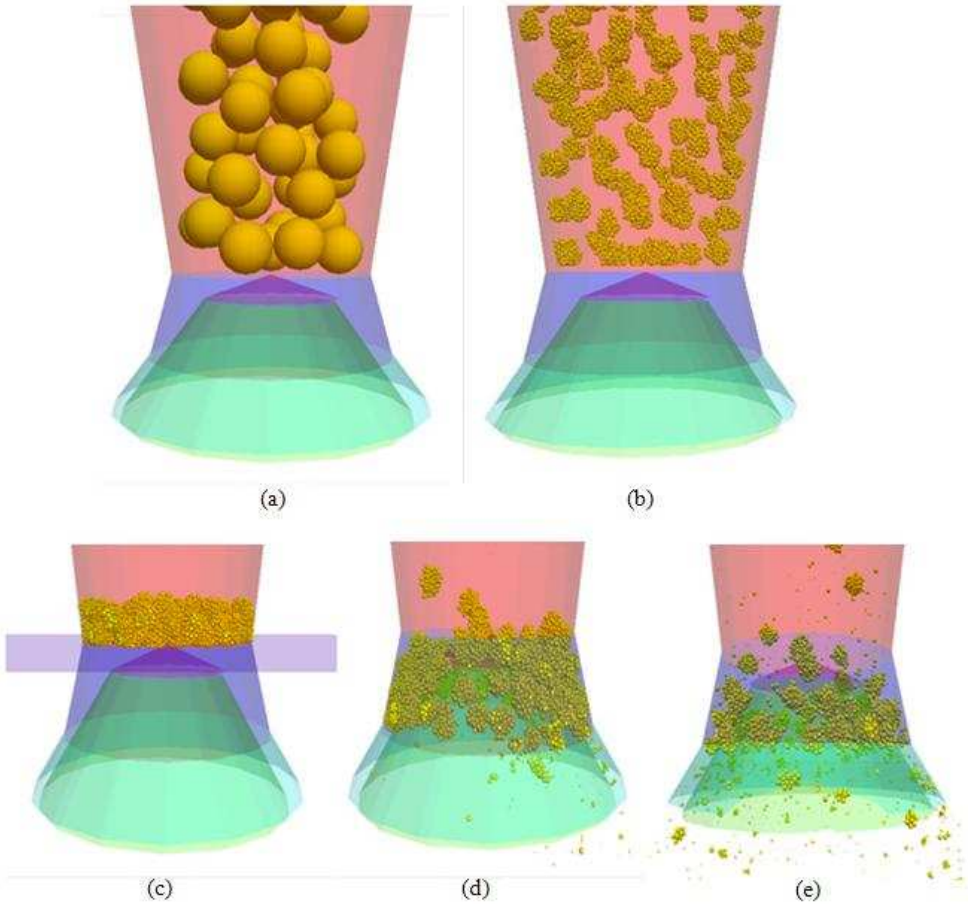

Figure 5Snapshots of the crusher simulation in action using BPM approach

Results

The sizes of the fragments were calculated as the equivalent radius, expressed as:

$$R_f = \sqrt[3]{\frac{3M}{4\pi\rho(1-P)}} \qquad \text{Equation 1}$$

where $R_f$represents the equivalent radius of the fragment and M denotes the cumulative mass of all the spheres included in the fragment, $\rho$is the density of micro spheres which is 2700kg/m^3 shown in Table 2, and P is the porosity of the initial agglomerate which is 0.31(Li et al, 2013).

The stills shown in Figure 5 show that some fragments are projected upwards out of the crusher chamber or bin, this dynamic phenomenon is caused by particle collisions and may also occur in the operation of real cone crushers. Figure 66 shows a graphical comparison of the predicted cumulative product size distributions for the two breakage models using the same cone crusher model geometry and operational conditions. The PBM curve is replotted based on Li et al (2014)' simulation result in which there are the same geometry of the cone crusher, the same eccentric speed and the same particle strengths. The CSS and eccentric speed were 15mm and 300rpm, respectively. An examination of the data presented shows that for any sieve size, the cumulative mass percentage produced by the BPM is always higher than that computed by the PBM. The largest differences between the predicted solutions occur at the finest size 2mm. The cumulative mass of products finer than 2mm for the BPM and PBM models are 9.8% and 0.5%, and this makes the BPM curve more consistent with a traditional product curve of cone crusher, Figure 7 (Hulthen, 2010) shows an example of product curves of cone crusher of various eccentric speeds in industry. The difference between the predicted distributions decreases for the largest particles sizes. It should be noted that the simulation of the crushing of the agglomerate feed in the cone crusher took 150 days on a PC with a specification of Intel(R) Core(TM)2 Q9650 up to 3.0GHz. The BPM method is therefore seen to be computationally very time consuming – the equivalent simulation using the PBM particle replacement method only took up to 20 days. However, the purpose of this paper has been a feasibility study to establish whether it is possible to model the crushing of particles of realistic shapes in a cone crusher and this has found to be possible and to give realistic results. This makes it possible to run simulations with different feeds and models and crusher geometries to establish which parameters can be adjusted to increase comminution efficiency and therefore inform design of new prototypes.

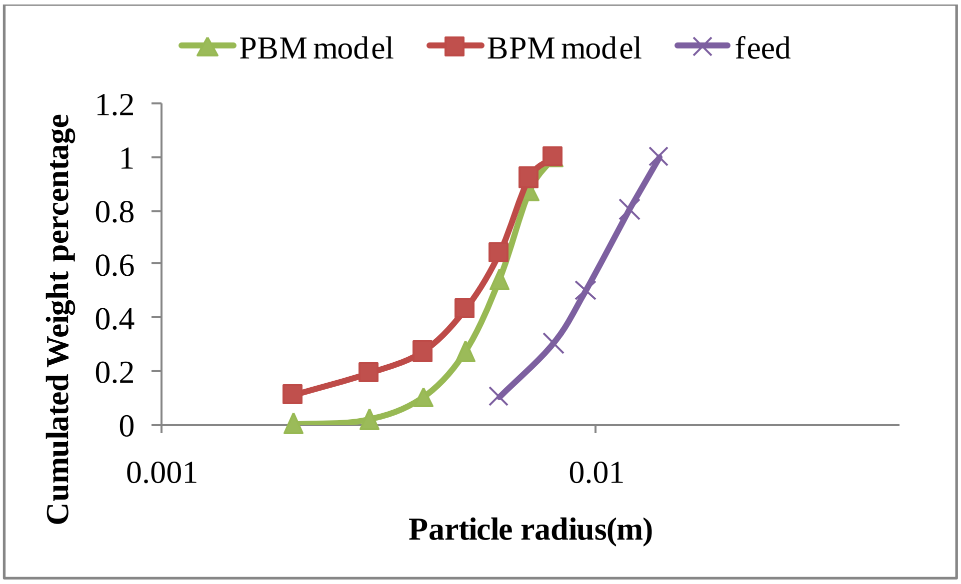

Figure 6 Comparison of BMP cone crusher and PBM cone crusher

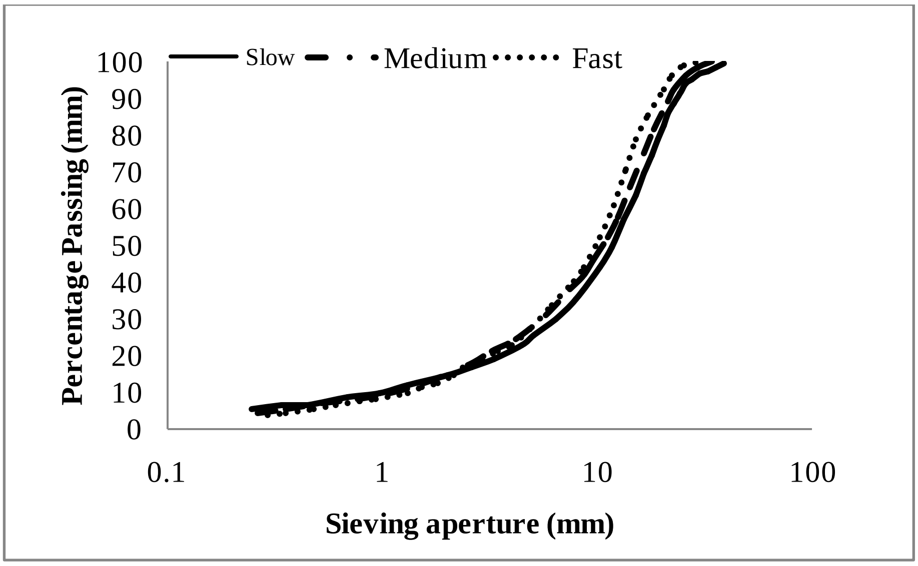

Figure 7 Traditional product curve of cone crusher (Data source: Hulthen, 2010)

Conclusions

A prototype DEM cone crusher model has been successfully constructed using the bonded particle model. The feed particles were represented by dense random packing agglomerates. The agglomerates were calibrated to have the same tensile strengths distribution with experimental diametrically crushed granite ballast particles. The comparison with PBM simulation results in literature shows the BPM cone crusher model was able to satisfactorily replicate the performance of a cone crusher. Thus it has been possible to model rock breakage in a comminution machine with an eccentrically rotating cone using alternative and complimentary methods, and modelling the fracture of irregular shaped particles using agglomerates of bonded particles has been shown to be possible. Based on the fact that the BPM model considers the particle flow as a result of crushing sequence and it provides more accurate results of fine products, it can be very useful even it consumes more computation time than PBM model.

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