Conveyor Belt Transfer Chute Modeling and Other Applications using The Discrete Element Method in the Material Handling Industry

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ABSTRACT

The proper modeling of granular flow using discontinum mechanics has the potential to be one of the most significant scientific advancements in the mining industry today. This paper will examine the status of discrete element technology, specifically focusing on current and future applications. The fundamentals of the Discrete Element Method (DEM) will be briefly introduced as well as relevant design parameters. Various types of granular flow problems currently being solved using the DEM methodology will be presented. The results and potential benefits of these cases will also be discussed. All simulation results and figures used throughout this paper are from studies and designs preformed by the DEM group at Conveyor Dynamics, Inc. (CDI).

1 INTRODUCTION

The DEM method is the name given to solution process by which the macroscopic properties of a system are determined by modeling its smaller individual components. Historically, the DEM method evolved from early molecular-dynamic algorithms and methods. The first DEM simulations used simple circular disks to represent individual particles or "discrete elements". This was entirely based on their mathematical simplicity. Contact algorithms for these particles were developed by Cundall & Strack (1979), and Walton (1982).

The basic solution methodology behind the DEM method is as follows. First, all of the relevant particle forces and interactions are determined. Figure 1 shows a simple type of contact model commonly used to model the behavior between two circular contacting particles. Simple springs, dash-pots, frictional sliders, and directional latches are used. This type of 2D model can also be extended into full 3D when modeling spherical particles.

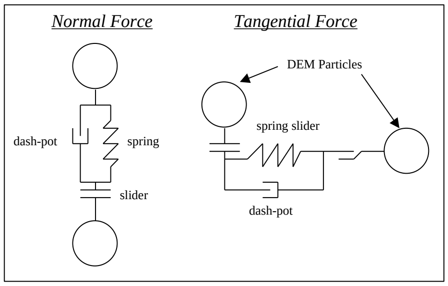


Figure 1 – Simple DEM contact model

Once the contact forces have been determined, Newton's 2nd law may be applied to determine the translational acceleration of the individual particle.

$$\begin{aligned} m\ddot{x} + c\dot{x} + kx - F &= 0 \\ m\ddot{y} + c\dot{y} + ky - F &= 0 \\ m\ddot{z} + c\dot{z} + kz - F &= 0 \end{aligned}$$

Likewise, Eulers equations of motion are used to determine the corresponding angular accelerations.

$$\begin{aligned} I_1\dot{\omega}_1 + (I_3 - I_2)\omega_3\omega_2 - M_1 &= 0 \\ I_2\dot{\omega}_2 + (I_1 - I_3)\omega_1\omega_3 - M_2 &= 0 \\ I_3\dot{\omega}_3 + (I_2 - I_1)\omega_2\omega_1 - M_3 &= 0 \end{aligned}$$

Using a time step *dt* and integrating the above equations in time, new translational and angular velocities can be calculated. Upon further integration new X,Y, and Z positions as well as the rotational orientation of the particle is determined. At theses new positions, the governing contact laws can again be solved thereby generating new contact forces. The entire solution process then repeats itself, and slowly progress in time at a rate *dt* per time step.

Although this general solution procedure has not changed dramatically since its introduction almost 30 years ago, the determination of the contact forces as well as the contact models themselves have varied significantly. Initially, only gravitational forces, particle-to-particles interactions forces, and particle-to-boundary forces were considered (as in figure 1 above). Recently however, a new generation of contacts laws have been derived to more accurately reflect the true physics of the particular problem under consideration. Current advancements include; cohesive & adhesive forces, breakage mechanics models and governing equations, fluid dynamic equations of state, and a plethora of others.

The rampant advancements in both computer power and memory has allowed the simple circular disk particle shapes to be replaced by much more complicated ones including multiple particle groups or “clusters”. Such clusters include: ellipsoids (Lin, 1993), Superquadrics (Barr, 1981), clusters of spheres (Qiu & Kruse, 1997), tetrahedrals (Potapov, 1994), and many others (Figures 2-4).

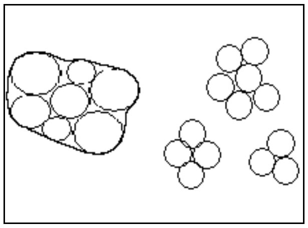


Figure 2 - Disk clusters

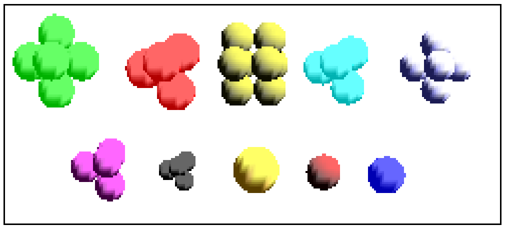


Figure 3 - 1,4,6,8 group particle clusters

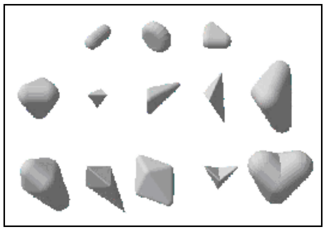


Figure 4 - Higher order shapes

Boundary surfaces can applied in a variety of different ways. For example, simple mathematical equations for lines and curved surfaces are often used. Other methods involve fixing or “gluing” particles to specific locations in space. Yet another technique, is to use triangulate surfaces as shown in Figure 5. The flexibility of triangular surfaces allow the users to generate almost any surface shape. Triangles are also very useful in the post processing stage to determine the impact and shear forces. Furthermore, triangles naturally lend themselves to easy visualization and computation.

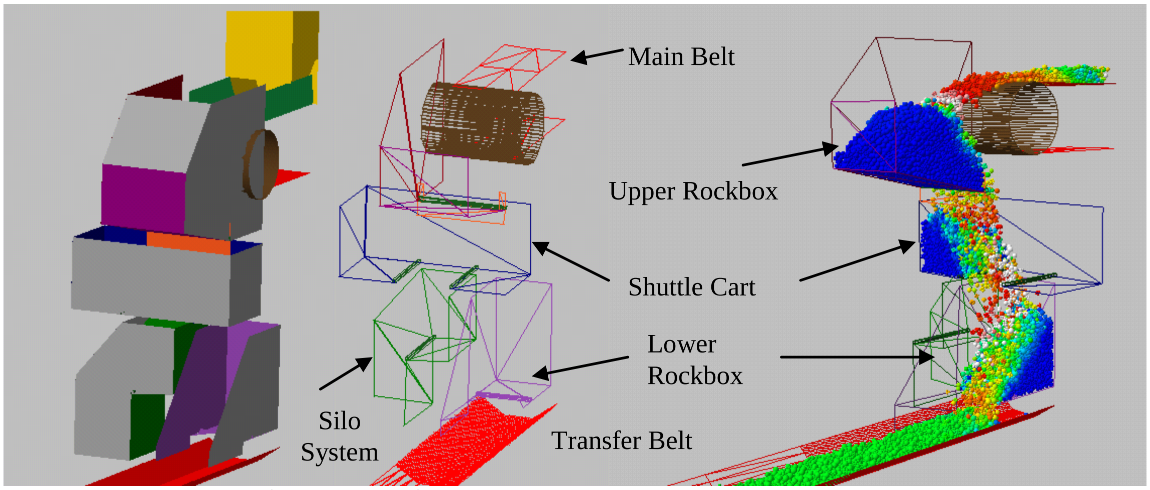


Figure 5 – DEM boundary surfaces & material flow

Particle-to-boundary contact laws may be the same or different, from the laws governing particle-to-particle interactions. Additionally, individual particle types may possess their own material and other internal properties. For example, in the steel ball mill simulation, the steel balls would obviously have very different properties from refined material.

This total flexibility inherent to the DEM method is by far its most tantalizing quality. By correctly modeling the individual properties of a system, it's complex, and often-chaotic behavior, may be analyzed, altered, and improved. The potential applications in the mining industry alone are enormous.

2 DEM PARAMETERS

Once the complex computer algorithms have been developed, the engineer must determine the appropriate input parameters for the problem at hand. Some of the most basic and fundamental parameters are: size and shape factors, bulk density, static and dynamic surcharge angles, cohesion & adhesion parameters, restitution coefficients, and fluid viscosity (if applicable). Many of these parameters are readily available or are given as a design parameter. Particle size distribution, for example, is routinely analyzed at many mine sites. Figure 6 shows an actual size distribution exiting a primary crushing facility and the corresponding particle sizes used in the DEM simulation.

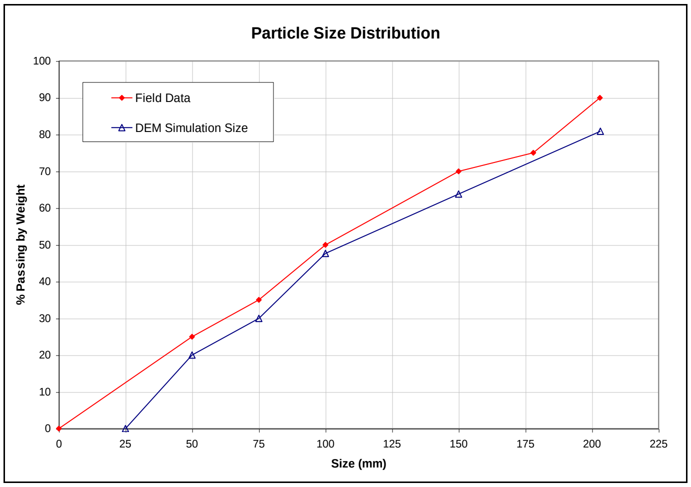


Figure 6 – Measured vs. Simulated Particle Sizes

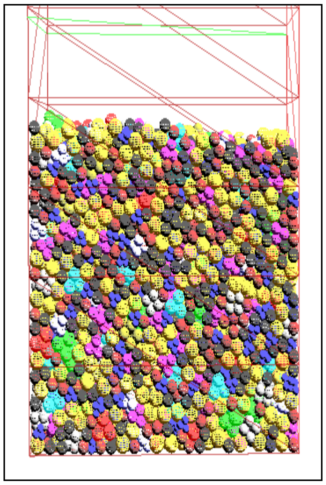


Figure 7 – Simple Bulk Density Test

Although the actual sized distribution approaches zero, a minimum DEM simulation size must be uniquely specified. It is important to note that as the size of the particles decreases, the number of particle increases. For example, if the particle size is reduced by a factor of 2 in a full 3-D simulation, then the number of particle required (and therefore the simulations time) for the same volume of material increases by a factor of 8! Fortunately, for most granular flow problems, the flow characteristics are largely determine by the particles greater than 10-20 mm in size. Particles under < 10mm in size generally have very little effect on the macroscopic behavior of the system. Furthermore, although fines may increase the internal coefficient of friction or cohesive properties of the material, these properties can be averaged into the larger particles to produce the same net effect. As computer power and memory advance an increasing number of particles may also be simulated.

Other relevant input variables can easily be verified by relatively simple tests. Bulk density, for example, is widely available for materials in the mining industry and can easily be calculated for most geometric shapes. When complex clusters are intermixed together a quick “packing“ simulation can be used to determine the proper bulk density (Figure 7).

Another easily measurable parameter is materials surcharge angle. Figures 8-11 show static repose angles for various particle groups and internal friction coefficients (f). Figure 8 shows the simulation of spheres with a typical or medium internal coefficient of friction. Figure 9 is identical to 8 except the spheres center of gravity has been offset by 90%, and a high frictional coefficient has been used. Figure 10 is comprised of single spherical particles with a medium frictional coefficient. However, in this case the particles rotational ability has been constrained. Figure 11 contains cluster groups of 1,4,6 and 8 spherical particles glued together.

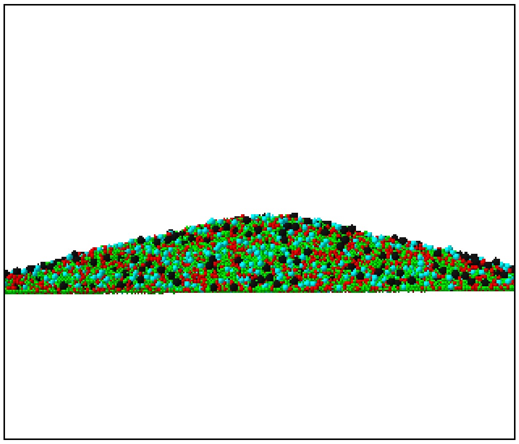


Figure 8 – Simple Spheres – Medium Friction

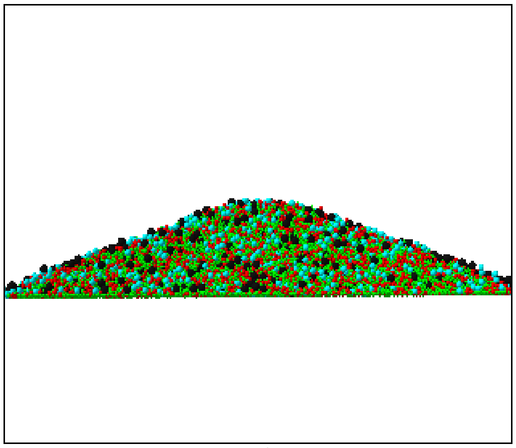


Figure 9 – Simple Spheres - Hi friction

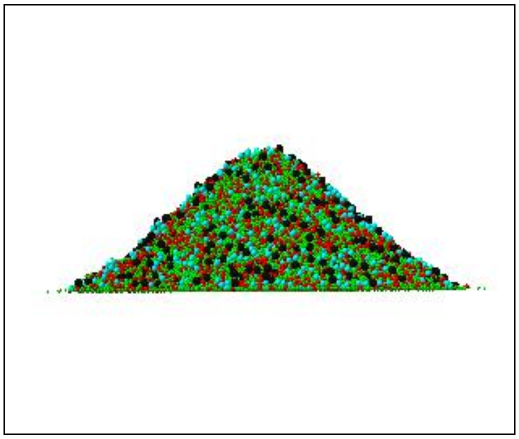


Figure 10 – Simple Spheres, Med. Friction, Rotation Constrained

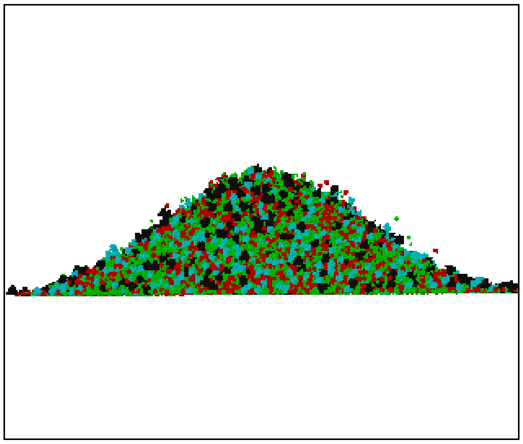


Figure 11 – Spherical Clusters – Medium Friction

The interlocking of the particles in figure 11 dramatically increase the repose angle and demonstrates the need to model higher order particle groups and clusters.

3 TRANSFER CHUTE DESIGN

3.1 Flowability & Visualization

One of the most fundamental and useful abilities of the DEM method is the visualization of material flows. Figures 12 & 13 show the results of various chute designs using the DEM method. The first, is a high speed transfer system (6.0 m/s & 8900 T/H), which was designed using the DEM method. Figure 13 is an example of a riling tower study conducted to determine both the flowability and the material degeneration encountered from numerous step geometry's and drop heights.

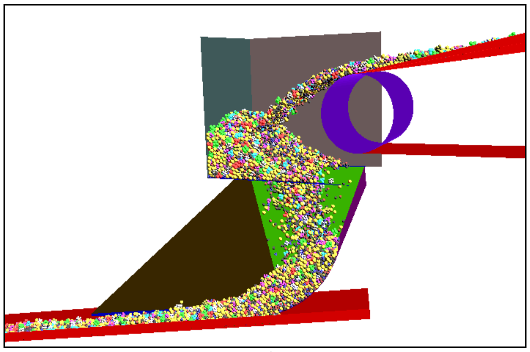


Figure 12 – High speed transfer system

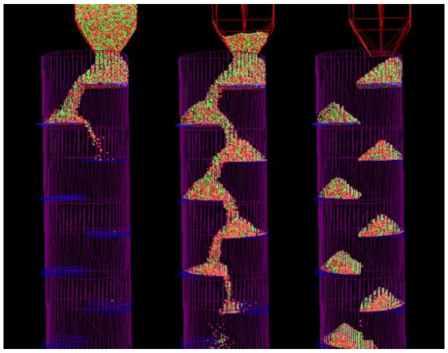


Figure 13 – Riling tower study

All too often engineering designs have been seriously restricted because the engineer is unable to visualize the final material flow pattern. Often, as in the case of material transfer stations, this results in over simplified designs where simplicity is gained at the expense of increased belt wear, excess material degradation, and decreased liner/chute life. If the engineer could only step back and visually see the material flow pattern a superior solution may present itself. The simple ability to accurately visualize a material flow pattern and concentrate on high wear locations and problem areas is invaluable. n many transfer applications material buildup and chute pluggage can be a major concern. The ability to simulate both "normal" material and highly cohesive or "sticky" material is of great value to the designer. Figures 14 & 15 demonstrate this concept.

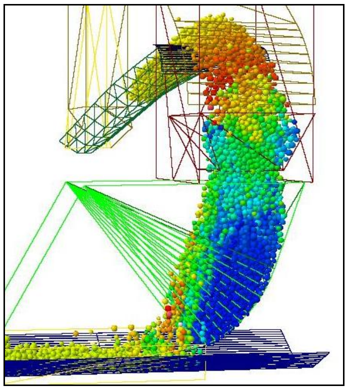


Figure 14 – Highly cohesive material

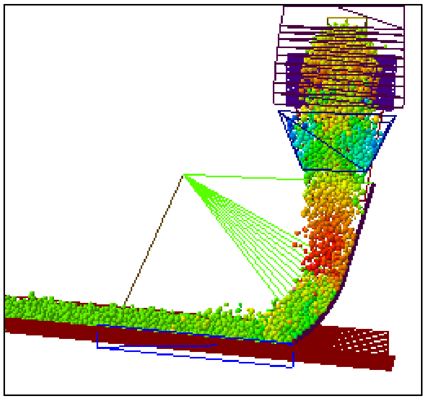


Figure 15 – Improved design to prevent material buildup

Although the flow pattern appeared acceptable for “normal” material flow, the chute plugged when modeled with highly cohesive material. By increasing the slope of the curved chute, and by slightly reducing the radius of curvature, this problem was solve. The material freely flowed though the entire system under all design cases (Figure 15). This ability to both simulate and visualize “worst case” scenarios is a luxury previous unavailable to the designer.

3.2 Material Degradation

In many granular flow problems the reduction or degradation of materials is of utmost importance. For the crushing and milling process, this is indeed the primary purpose of the operation. However, in other processes such as coal briquette transfer chutes, it is important to handle the material as gently as possible. The inherent computational nature of the DEM method, ideally lends itself to solving these types of problems. As discussed in the introduction, the DEM simulation calculates all relevant forces on each particle in the flow stream. During the computational process this information can easily be stored for later analysis. Various statically averaging techniques and other post processing methods can then used to examine various items of interest. Two commonly investigated parameters are the normal and shearing work acting on particles.

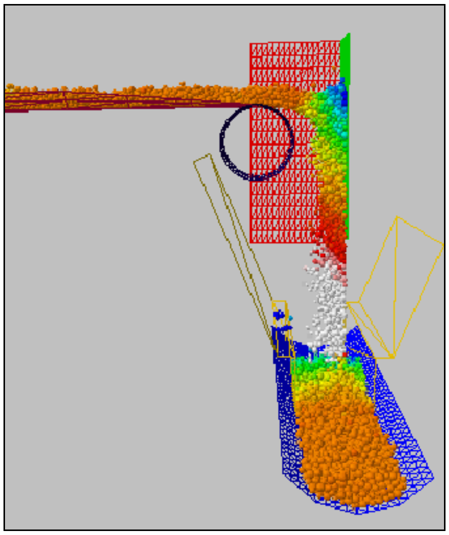


Figure 16 – Flat plate transfer

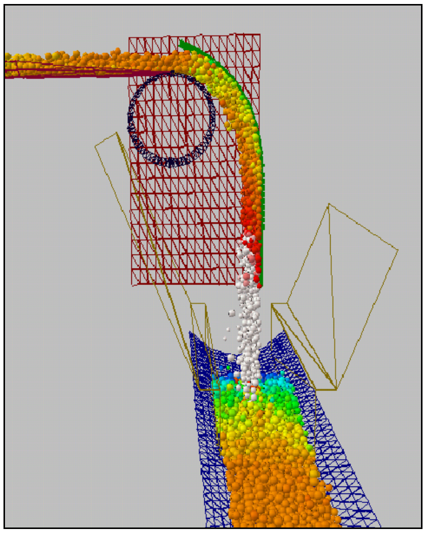
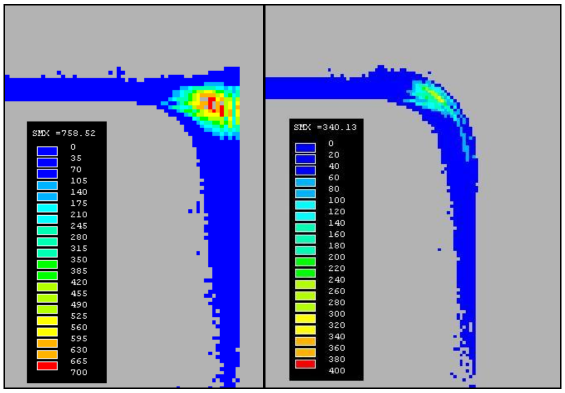
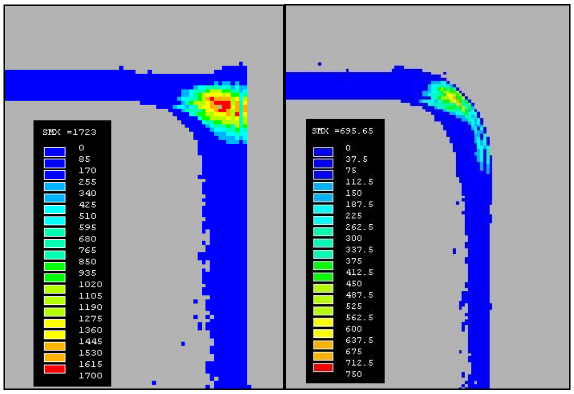


Figure 17 - Curved hood transfer

Figures 16 & 17 show two distinctly different transfer methodologies. The first, allows the material to directly impact upon a flat plate. The impacting material develops a stagnation zone (shown in blue) and a “rhino-horn” flow pattern develops. Conversely, in figure 17, an upper curved hood is used to gently bend the flow 90 degrees. For this particular material both liner wear and material degradation were of concern. Figures 18-21 were generated by averaging both the normal impact work and the shearing work between particles once steady state flow had been achieved. The impacting forces imparted to the particles was found to be approximately 4 times greater for the flat plate compared to the curved hood. Furthermore, the shear work generated from the flat plate flow was approximate double that of the curve chute.



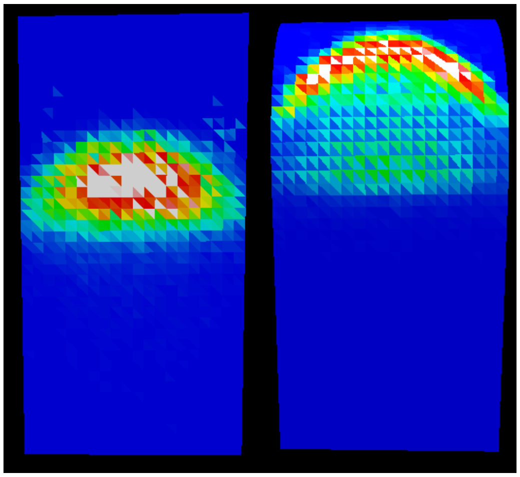
Figures 18 & 19 – Particle impact work



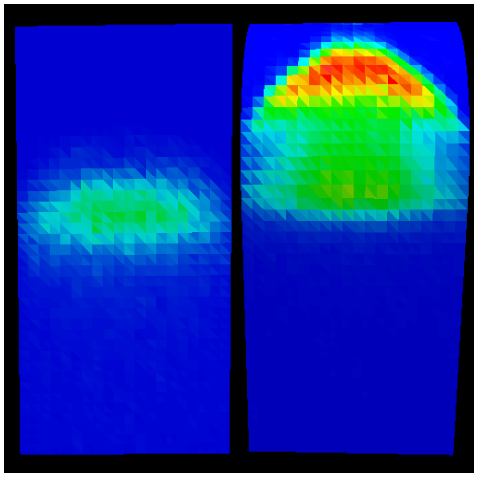
Figures 20 & 21 – Particle shear work

Although it may be obvious that the curved hood should indeed provide a much gentler transition than the abrupt flat plate, the ability to quantify such effect is of great importance. Furthermore, and much less obvious, is the simple question “What hood curvature would develop the least amount of wear while still minimize particle degradation?”. This is the type of question at which the DEM method excels. By keeping all other factors constant (friction factors, material size distribution, tonnage, etc.) the designer can specifically focus on how geometric modifications influence the flow, wear, and material degradation.

Another result which is naturally derived from the DEM method is the containment or boundary surface forces. Particle-to-boundary forces are obtained in a similar methodology as used to determine the particle-to-particle forces. Figures 22-25 show the results from the same DEM simulation as in figures 18-21.



Figures 22 & 23 - Impact wear on flat plate and hood



Figures 24 & 25 - Abrasive wear on flat plate and hood

Although the material impact forces for the curved hood are lowered than the flat plate, the shear work is significantly greater. For this particular case, a tradeoff had to be made between the cost benefits incurred by the reduce material degradation, and the potential cost increases for maintenance/replacement of the hood. In this case the curved hood was chosen. Additionally, a study is underway to determine the possibility of installing a lower curved chute system to prevent further material degradation of the material as it impacts the receiving belt.

3.3 Belt Wear

For many conveying systems, the cost advantages are not related to material degradation or chute wear, but governed by the extremely high replacements cost of the receiving belt (Nordell, 1994). It is therefore essential to maximize a belts life as much as possible. Material transfer stations are often the main source of belt damage, and therefore must be designed to minimize damage to the receiving belt. The goal is how to rotate the material flow into the receiving belt direction and, at the same time, accelerate it as close as possible to the receiving belt velocity.

Although the belt is moving, the solution process for determining belt wear is identical to the particle-to-boundary technique discussed above. Figure 26 show a simulation using a typical rockbox design. This type of transfer is widely used in the conveyor industry due to its simplicity. The material essentially stalls, and the horizontal velocity is almost zero. The material simply builds up in the rockboxes "dead zone" and then rolls down landing directly on the belt. Due to the flows low horizontal velocity, high shearing forces are generated between the material and the receiving belt. This results in substantial abrasive damage to the receiving belt.

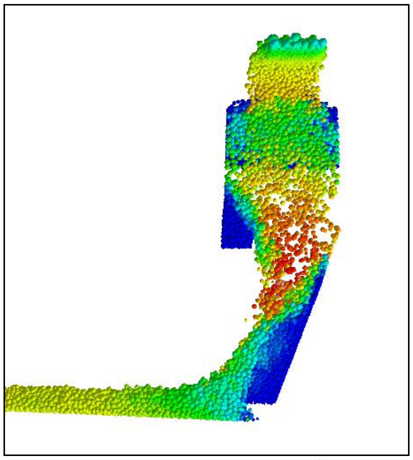


Figure 26 – Typical Rockbox Transfer

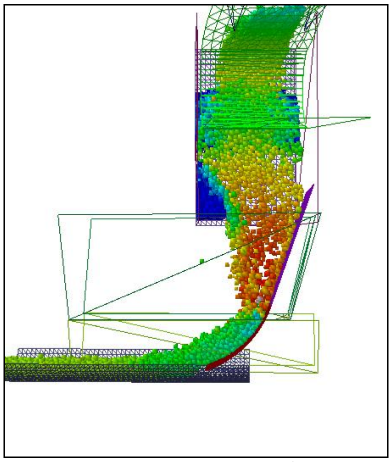


Figure 27 – Curved Chute Transfer

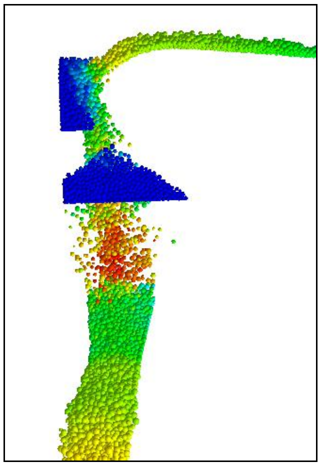


Figure 28 – Curved Chute Front View

In the curved chute case however, the material is rotated in the horizontal direction and the energy/velocity generate by the material falling is conserved. This greatly reduces the shear work required to accelerate the material back up to full speed. This in turn significantly decreases the amount abrasive damage incurred to the receiving belt. Figures 29-31 show a comparison between the shear forces generated by the curved chute and those generate by the rockbox. In this particular case, the curved chute reduces the shear work by a factor of 5 over the original rockbox design!

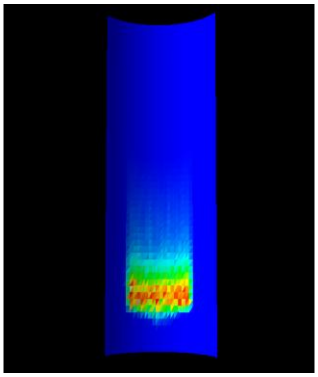


Figure 29–Rockbox Wear

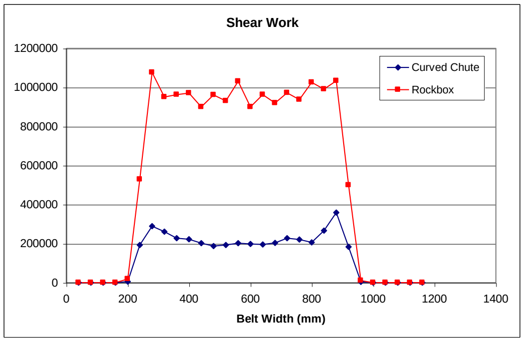


Figure 30 – Rockbox & Curved Chute Abrasive Wear

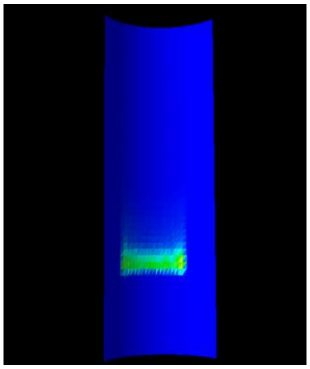


Figure 31-Curved Chute Wear

These benefits are not however without their disadvantages. Generally, curved chute are more expensive to both design and build than their rockbox counterparts. Additional, they may incur higher maintenance costs and wear rates. However, many installations are consistently battling with material plugging and other maintenance factors which may be completely eliminated by the installation of a curved chute. For many of these installations the cost saving of a curved chute system can be enormous. Whether or not a curved chute is right for a particular application is difficult to determine until a proper analysis is preformed. The important point for the designer, is to simply keep in mind is that these type of analysis tools exist. A wide variety of transfer systems have been already been designed using the DEM method. Furthermore, as DEM continues to evolve and become more powerful these type of simulations will become the norm rather than the exception.

3.4 Pollution Control

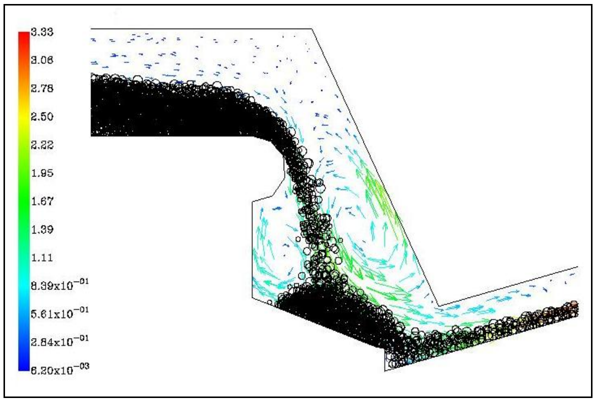


Figure 32 – Airflow velocity vectors

Another application of DEM technology in transfer chute systems, is pollution control. Although the specifics of this technology is outside the scope of this paper, analysis methods have been developed to determine both the pressure and velocity distribution of the surrounding air mass. This allow the designer to determine the potential pollution effects of one design as opposed to another and in the strategy of equipment and dust collection systems. Figure 32 shows the airflow velocity vectors for a typical rockbox transfer system.

4 MILLING INDUSTRY

As the reader may be discovering, the DEM methodology lends itself extremely well to many areas in the mining industry. Yet another area of current research is in communition circuits. For some time “dry” mills have been simulated using the DEM method. A dry air flow mill is a primary example. For most autogenous and semi-autogenous mills, the ability to model both solid and “fluid” behavior is essential. Therefore, the fundamental equations needed to be revisited and coupled with computation fluid dynamic (CFD) equations. These complex theories require papers within themselves and the readers may look to Potapov et al. (1995), Tsuji et al., (1993), Xu & Yu (1995), and others for more information on them. Instead the visualization results from some typical mill simulations performed by CDI will be presented.

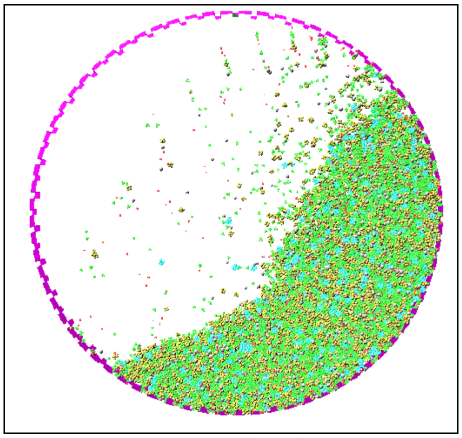


Figure 33 – “Dry” AG mill simulation

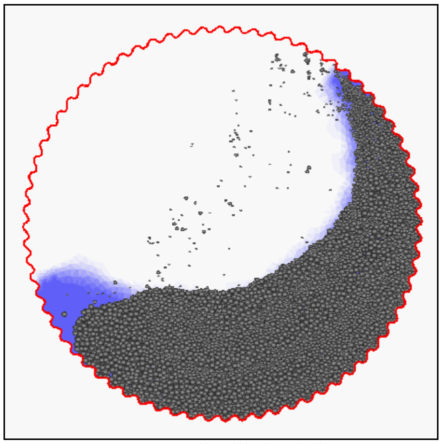


Figure 34 – “Wet” Ball mill simulation

The two figures above show the material flow behavior in both a “dry” and “wet” mill simulation. Approximately 70,000 particles were used in these full 3D simulations of a 36 ft. diameter mill. A 0.5 meter cross sectional slice, using periodic boundary conditions, was used for these simulations. Figure 35 shows a velocity vector profile of the complex material shape developed inside of the mill during operation. Figure 36 show the internal shear forces generated between particles. The possible advancement in this area are staggering. Not only are material degeneration properties calculated, but also lifer and grinding media wear, consumed power, and other extremely useful quantities are obtained.

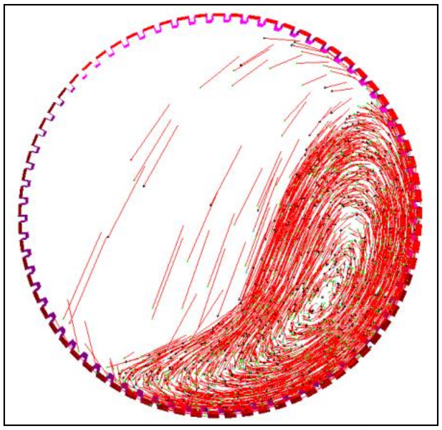


Figure 35 – Velocity vector tail showing flow pattern

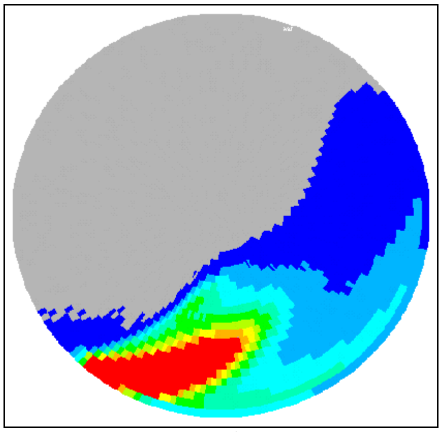


Figure 36 – Particle shear force generated inside the mill

5 CRUSHING

Like milling, the crushing industry is primarily concerned with particle size reduction. It too has the potential to be improved though a different type of DEM simulation. Figures 37 & 38 show a particle fracture application not normally associated with the DEM method. However, like the chute flow or other cases presented earlier, these models are initially comprised of thousands of individual DEM elements.

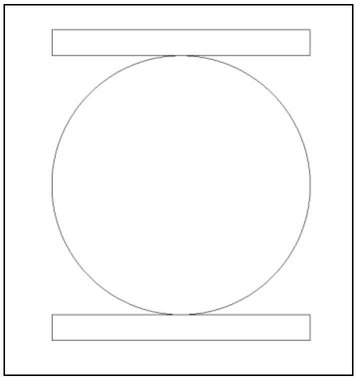


Figure 37 – Initial geometry

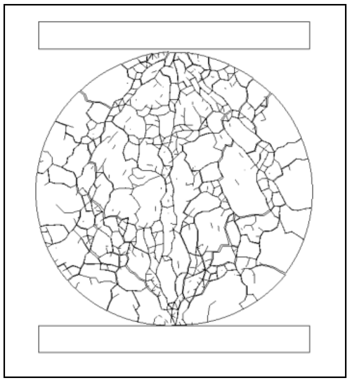


Figure 38- Final geometry

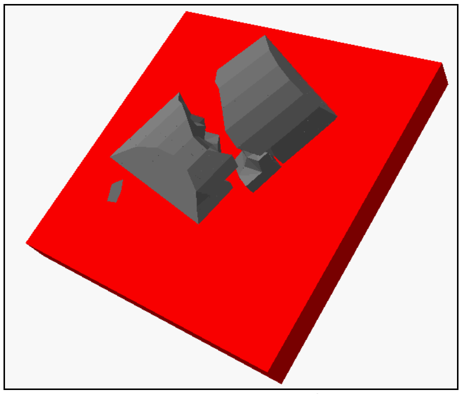


Figure 39 – 3D breakage model of an iron briquette

As with the simple 2D disks which evolved into 3D spheres, these breakage mechanics models may also be extend to full 3D. Figure 39 shows a coal briquette being shattered in a full 3D breakage mechanics simulation.

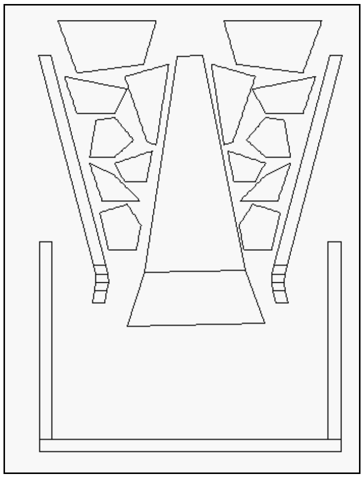


Figure 40 – Crushing Simulation t=0.0

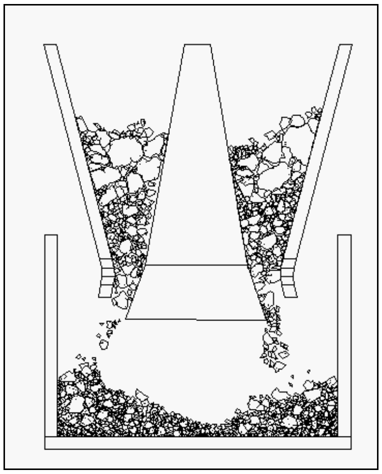


Figure 41 – Crushing Simulation t=7.0

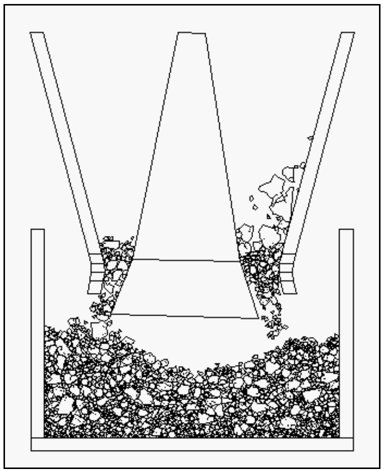


Figure 42 – Crushing Simulation t=15.0

Figures 40-42 show a 2D simulation of a gyration crusher. Size reduction, material flowability, and power requirements are just a few of the many potential results obtained from such simulations.

6 CONCLUSION

This paper has briefly touched on just a few of the areas where the DEM methods has been applied. However, the potential applications stager our imagination. For years the mining industry has taken a trial-and-error approach to many system designs. Advancements and modifications have progress gradual and very slowly. By no means will DEM technology revolutionize the mining industry overnight. However, if we can couple years of hands on experience and historical data with new, and ever improving DEM technology, a “key” will be given to us. But it will be up to us to use this “key” and open the door to new designs and future technology.

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