IMPLEMENTATION OF A DISCRETE ELEMENT METHODOLOGY FOR THE MODELING OF GRAVITY FLOW OF ORE IN ORE PASSES

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ABSTRACT: Many industries store and handle solid materials in bulk form. When the volume of the solids is large, industry invariably relies upon the gravity to induce the solids to flow out of storage, through channels and reactors. As an example production in most deep underground mines depends on the safe and continuous operation of ore pass systems. Their requirements to less energy (only gravity) have made them very popular not only in underground mines but also in open pit mines. This paper discusses the major findings of research on 2D Discrete Element Method (DEM) simulation of gravity flow of ore in ore passes. The study shows that ore shape, ore pass configuration and the existence of a Dogleg can significantly affect loads (static, dynamic) on the ore pass gate assembly and creation of hang-ups.

1. INTRODUCTION

If we define an underground mine as a factory where men and equipment produce ore, in this context an ore pass is an element in the handling system, which also consists of stopes, possibly a crusher, conveyor belt, loading chute and the mine shaft. The configuration, size and purpose of ore passes vary widely. They may be vertical or inclined, straight or doglegged, circular or rectangular in cross-section, designed for intermediate storage, or as a chute, Figure 1.

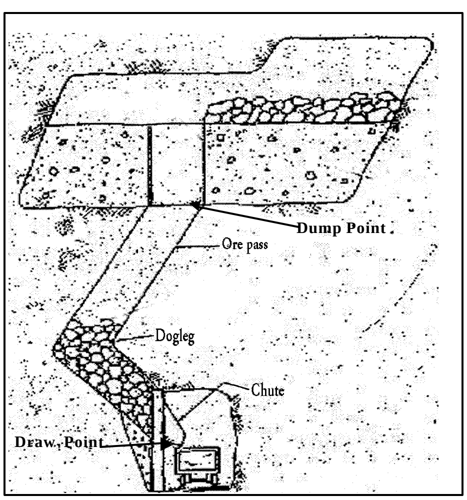

Fig. 1. Schematic of an ore pass system

Chronologically, construction of an ore pass is the last step prior to producing the ore. Given time constraints from the pressure to produce, industry often pays inadequate attention to details concerning ore pass location and design. Consequently, it is not surprising that ore passes frequently present problems or even fail.

Ideally, an ore pass should be considered a permanent opening, which, along with the main transportation shaft, comprises the main artery sustaining the economic life of a mine. Ore pass hang-up, or blockage requires extensive rehabilitation involving extraordinary expenditures while interrupting production and decreasing revenue since fixed operation costs remain constant, [1].

Although ore passes, chutes and gate systems for mining of metal and non-metal mines must meet the requirements specified in the U.S. Code of Federal Regulations (CFR), part 57 and 75, the MSHA database (1987-1996) on accidents and fatalities related to failure or hang-up of ore passes, reports a total 743 nonfatal accidents (e.g., permanent disability, injury, occupational illness) and eight fatalities.

There are two major types of hang-ups as follows, [2]:

- Hang-up where large-sized boulders become wedged together to form interlocking arches.

This occurs when the relatively few larger fragments form stable hang-up arrangements in the ore pass. The occurrence of this type of hang-up could be enhanced by abrupt changes in ore pass geometry. The possibility of forming such arches depends on the percentage of large size particles in the material handled, on the size of the particles relative to the size of the ore pass and outlet, on the shape of the rock fragments, and on the velocity profiles across the flowing ore.

- The cementation effect of fine and sticky particles (d<0.254 mm) may create a cohesive arch type of hang-up. The presence of moisture in the bulk ore mass will also increase cohesive resistance of the arch. The mining industry relies on a few functional design factors to avoid blockage of materials in an ore pass. They are mostly based on empirical equations and applications of elementary mechanics of materials. These factors are summarized in Table 1.

Table 1. Ore and ore pass characteristics for hang-up avoidance (after Hambley, 1987)

Dimensional requirements	**Type of hang-up that could be avoided**
$D/d>5$	Interlocking arches
$D_o>3d$	Interlocking arches at outlet
$H=0.8\ D_o$	Hang-up at chutes
$D\geq(0.32\ C_o/\gamma)(1+\csc\phi)$	Piping (funnel flow)
$D>(0.61k/\gamma)(1+1/r)(1+\sin\phi)$	Cohesive arches

D= Ore pass diameter (m)
D_o= Width of the outlet (m)
C_o= Compressive strength of the fines (Pa)
ϕ = Angle of internal friction of fines
d= Maximumore dimension (m)
H= Chute height (m)
γ= Density of fines (kg/m^3)
k= Cohesion of fines (Pa)
r=Ratio of opening width to its length

To study the flow of ore in ore passes, experiments by analogy with flow of other materials, full-scale field studies and numerical modeling are the potential methods. Analogy of ore flow with other materials such as sand could not be done precisely because of ore shape, size, discharge rate and boundary conditions in ore pass operations are not analogous to experiment conditions. Full-scale field studies are generally very expensive; they create interruptions in regular mining operation and production, and could provide only localized information.

Among different methods of numerical modeling, the DEM due to its ability to simulate accurately the mechanical behavior of granular ore materials has been selected.

The main objective of the research study which current paper is presents its results, were the development, application and validation of a numerical methodology to study the operational performance of ore passes which include better understanding of ore flow behavior in ore passes and conditions for occurrence of interlocking type hang-ups.

2. MODELING GRAVITY FLOW OF ORE

2.1. Discrete Element Method (DEM)

DEM is the numerical procedures for simulating the complete dynamic behavior of discrete, interacting bodies. Each individual particle (body) with general shape (deformable or rigid) based on its unique characteristics can be subjected to gross motion.

Engineering problems such as the flow of granular materials, which exhibits very large-scale discontinuous dynamic or static behavior, cannot be solved with a conventional continuum-based approach such as the Finite Element Method.

DEM has provided a numerical means for analyzing the progressive movements and interactions of bodies in granular assemblies. Its algorithm applies Newton's second law to each particle within the system. The continual movement of each body results from the non-equilibrium of different forces exerted on it. DEM explicitly models the dynamic motion and mechanical interaction of each body at discrete points in time, with each point being termed as a time step. For this purpose, integration of equations of motion and contact laws is necessary. This is the heart of each DEM code, and is the most time intensive part (computational timing).

DEM modeling of granular media is often performed using a system of 2D circular (disk) elements. Disk elements offer several advantages such as: relatively short computation time, and simplicity of contact detections and contact force calculation. But disks can roll excessively, and they demonstrate lower peak friction angles than real materials, [3].

Basically, it is difficult to simulate real material behavior when the ore is even slightly angular. In the current research, a cluster version of DEM code has been developed. The Cluster-2D code combines the simplicity of dealing with circular disks and the accuracy of modeling ore shape. Each cluster consists of the desired number of disks, connected rigidly together in a specified manner. Figure 2 shows a rectangular-like cluster of six disks, [4].

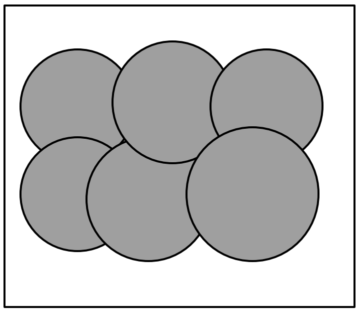

Figure 2. Cluster of six circular disks

The governing equations for any cluster of (n) circular disks based on Newton's second law can be presented as:

$$M = \sum_{i=1}^{n} m_i \quad (1)$$

$$I = \sum_{i=1}^{n} \left(m_i d_i^2 + m_i \frac{r_i^2}{2} \right) \quad (2)$$

$$I_G \ddot{q} = \sum M_G \quad (3)$$

Where m_i is the mass of the i^{th} disk, M is the mass of cluster, I is the mass moment of inertia of cluster about its center of mass (G), I_G is the polar moment of inertia of cluster, $\ddot{q}$ is the angular acceleration of the cluster, M_G is the total moment of cluster with respect to the center of mass, d_i is the distance from the G (center mass of cluster) to the centeroid of i^{th} disk, and r_i is the radius of i^{th} disk.

A number of researchers [5] have emphasized that in the case of a conical hopper, there is a good correlation between results from two-dimensional simulations and their three-dimensional counterparts. Due to the similarity with the configuration of ore passes (very long in one dimension compared to their cross sectional) loading on ore pass gate should be comparable in 2D and 3D simulations.

DEM simulation of ore passes proved that in qualitative terms there is agreement in predicting similar hang-up conditions in 2D and 3D simulations, [6]. The above rational justifies the application of a two-dimensional computer program to study the gravity flow of ore in ore passes. Note, to quantify the differences between two-and three-dimensional ore flow needs further investigations.

A 2D numerical model based on Discrete Element Method (DEM) has been developed to study different problems concerning gravity flow of ore in ore passes. This model, with use of a rigid and cemented cluster of disks can simulate different ore shape and its angularity as well. The modeling parameters for the ore and ore pass were considered to be as follows:

- Ore pass inclination, coefficient of friction (ore/wall), different dumping points design, stiffness of wall and existence of Dogleg, and,
- Ore shape and size distribution, coefficient of friction (ore/ore and ore/wall) and stiffness of ore material.

The research focused on the effects of ore pass configuration and ore characteristics on the most important aspects of ore pass design as follows:

- The dynamic and static loads on ore pass gate assemblies, and,
- The flow regime of ore in ore passes with specific interest to creation of hang-ups.

The terms dynamic and static loads refer to the maximum normal impact load on the bottom gate of the ore pass, and the steady vertical load on the bottom gate (proportional to the weight of ore).

2.2. Ore and Ore Pass Shape/Size Characteristics

The prediction of shape and size distributions of ore after blasting, are very important and critical steps in most mining operations, which strongly influences the subsequent steps of digging, hauling, transporting, and crushing. Furthermore, proper consideration of ore/waste size and shape distributions can bring tremendous savings in energy and cost to a mining operation. But due to its unpredictability at least with the current level of technology, there is not a general method of measurement.

Yet all researchers agree that the concepts of shape and size are interrelated. The length and width are referred to as sizes (2D dimensions), but they may also be used as a factor to describe the shape of particles (elongation/aspect ratio).

According to these consideration, and extensive literature reviews and mine visits [7], for modeling purposes three ore-cluster shapes are defined and applied in different simulations. These are crude shape descriptions of the ore-clusters and even can be used in combination to model a specific shape of ore. Figure 3 is an example of blasted ore passed through an ore pass and Figure 4 illustrates the implementation of different ore shapes in the DEM modeling.

Fig. 3. Blasted rocks in Henderson mine
(Mine Visit Sept. 2000)

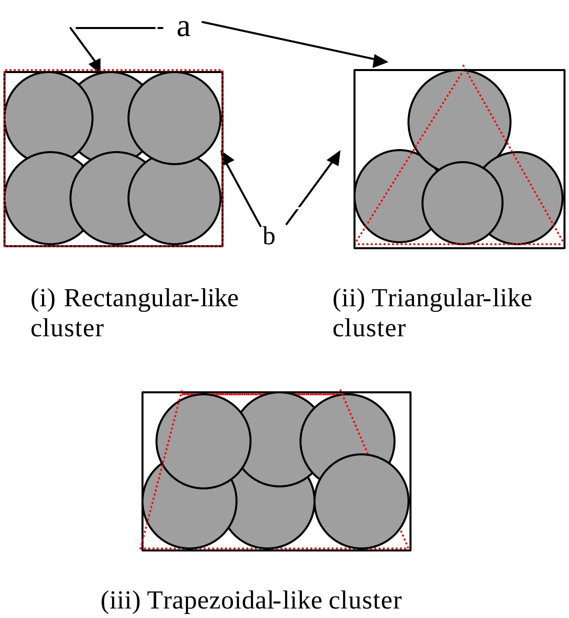

Fig. 4. Three different shapes of ore-clusters

For calculation of shape parameter (reflection), a rectangle is assumed to be circumscribed to the longest dimension of the ore-cluster. The aspect ratio (elongation) of the ore-cluster would be $e = \frac{a}{b}$.

The index for the angularity of an ore-cluster is defined as the ratio of the area of cluster to the area of circumscribed rectangle. This value varies from 1.0 (for a shape without abrupt angularity or rectangular-like clusters) to 0.5 (a shape with extreme angularity such as bisectors triangular-like cluster).

With respect to the available information from different ore pass operations and previous experience [7] maximum size of an ore-cluster (dry and cohesionless) about 0.1m with a maximum size-deviation of 15% were decided. Figure 5 illustrates the general ore pass configuration.

Primary simulations indicated that a height to diameter ratio of 25:1 allows enough time for flow of ore-clusters building up the incremental friction forces. Note these DEM simulations had a run time in range of 1.5-3.0 days (CPU time). In order to model the actual loading/dumping of ore materials more closely, and also to avoid non-physically high dynamic load due to direct impact of ore material on the pass bottom gate, a feeder with an inclination of 60^0 is defined at the dumping point.

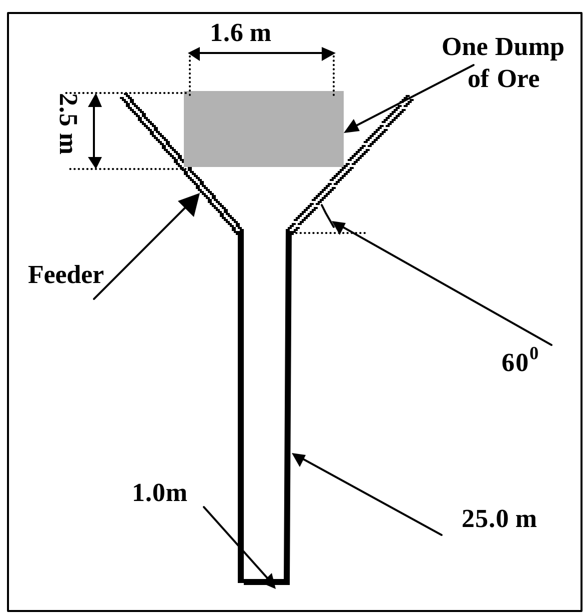

Fig. 5. Ore pass configuration (not to scale)

3. ORE PASS SIMULATION

3.1. Loads on Bottom Gate

Current research has focused on simulations of conditions for safe performance of ore passes. In this respect, the static and dynamic load on gate assembly of ore passes, which is loaded with 10 equal dumps of ore (cohesionless and dry), would be considered. The impact factor is defined as the ratio of total normal load on the bottom gate of ore pass at any moment to the total weight of ore.

The gravitational acceleration is assumed to be 9.8 m/s^2 and the coefficient of friction if not specified is equal to 0.6. The coefficient stiffness of system [7] is calculated equal to 1.2 X 10^8 N/m and coefficient of restitution equal to 0.2.

To prevent spiky behavior of load-time history data obtained from a DEM simulation and making it more comparable to data from measurement, the time-averaged load concept is applied [6]. In this method, the DEM load calculations (impact factor graphs) are smoothed over intervals (0.01-0.02) seconds.

The following describes the results of DEM simulation which was performed in order to study effect of:

- Different ore-cluster shapes, and
- Various coefficients of friction.

Figure 6 illustrates the direct relationship between peak load and static load and the defined angularity of ore-cluster. For the higher angularity (Triangular-like cluster), these values are lower compared with the lower angularity (Rectangular-like cluster). Because non-circular particles at the interaction point have more shear strength, as a result the impact velocity would be lower.

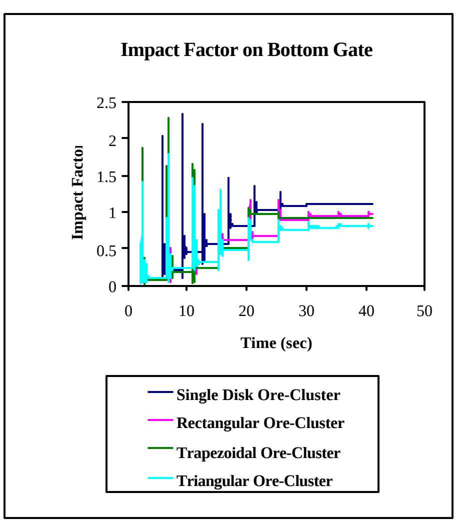

Figure 6. Impact factor on bottom gate for different shape ore-cluster

Figure 7 shows the effect of change in the coefficient of friction on dynamic and static loads on the bottom gate of ore pass. For the higher coefficient of friction during period of collisions (ore-cluster/wall, ore-cluster/ore-cluster) the ore-clusters will lose their kinetic energy more and quickly. This reduction in impact velocity along with higher shear forces between walls and ore-cluster also reduces the static load on bottom gate.

Figure 8 illustrates a series of snapshots of ore flow, which for the lowest coefficient of friction; the ore-clusters did not disperse and generally acted as a block.

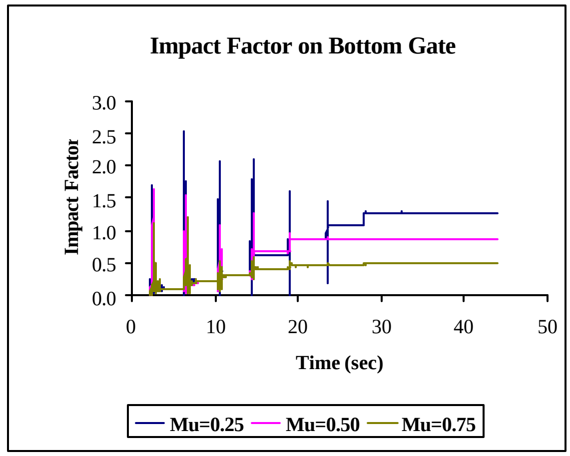

Figure 7. Effect of coefficient of friction on bottom gate impact factor

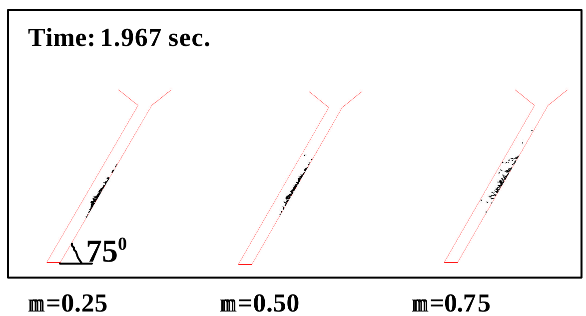

Figure 8. Flow of ore-clusters with different coefficient of friction

3.2. Ore Pass Simulation, Flow of Ore in Ore Passes

To investigate flow of ore in ore passes, an ore pass configuration has been filled with 10 equal dumps of ore-cluster materials. Then the bottom gate was allowed to be open suddenly so that the ore material could flow into the horizontal drift.

The following results present the results of DEM simulations of ore flow to study effect of:

- Existence of Dogleg (abrupt change in inclination of ore pass at the bottom part).
- Various coefficients of friction.

Higher inclined ore passes generate free and fast flowing ore. However, the faster ore flow may cause severe damage to the ore passes walls and gates. To accomplish a balance between these two opposing effects, an ore pass can be designed with a Dogleg section, which is an abrupt change in the inclination of ore pass.

Adding a Dogleg section to an ore pass system, will allow the mine to benefit from the free and fast flow of ore and a reduction of dynamic load. This can also help to simplify and reduce the cost of the design for the gate facilities. On the other hand in some cases a sudden change in the inclination of an ore pass may create other problems, such as hang-ups.

Figure 9 shows the results of mass-flow measurements for different configurations of Doglegs. At 40^0 inclinations, blockage of ore has completely stopped the flow of ore out of ore pass within two seconds and 35% of ore was blocked in the top of ore pass. Figure 10 illustrates the creation of a highly compressive stressed zone (interlocking arch) due to weight of ore-cluster at the top of Dogleg section around the hung-up area.

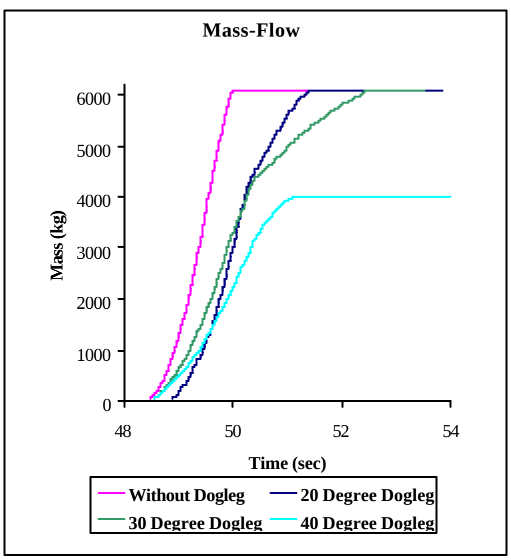

Figure 9. Effect of different configuration of Doglegs on mass-flow out of ore passes

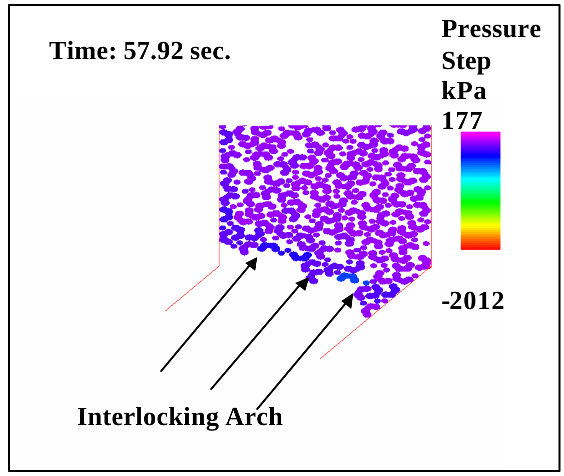

Figure 10. Average stress distribution (not to scale)

Friction has a major impact on flow of ore in ore passes. Note, friction forces along with damping forces, are responsible for a significant of loss in kinetic energy of gravity flow of ore. In DEM simulations of dry and cohesionless materials this effect becomes much more pronounced.

Figure 11 shows the snapshots of the ore flow after opening the gate at the end of simulation (time: 48.8 sec). These simulations were performed with the coefficients of friction equal to 0.25, 0.50, and 0.75 respectively. It illustrates the effect of high coefficient of friction and clogging of ore at the bottom of ore pass where the coefficient of friction was 0.75. Also it presents the effect of coefficient of friction on angle of repose.

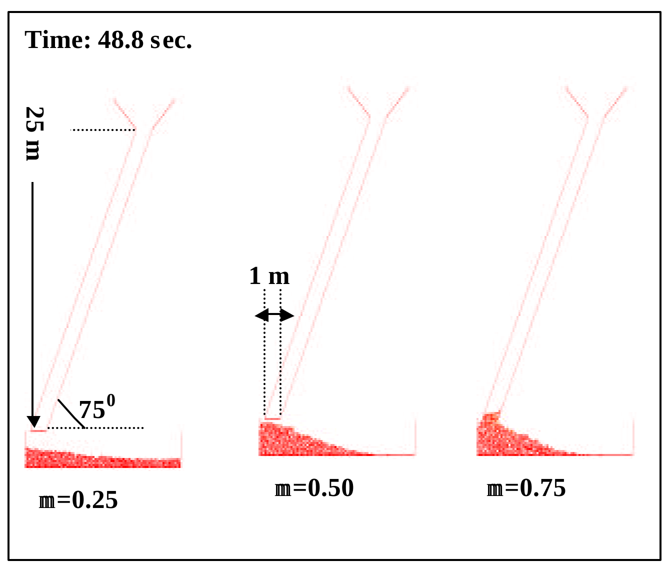

Figure 11. Snapshots of ore flow for different coefficient of frictions (not to scale)

4. CONCLUSIONS

This research demonstrates that a rigid cluster based DEM computer code could predict loads, stresses on gate assemblies/walls and ore flow in ore passes. The examples were presented for demonstration of applicability of DEM techniques to better engineering analysis of ore pass design. The results illustrate the importance of ore shape on static and dynamic load on ore pass gate assemblies.

Simulation results demonstrate the necessity to revise some of empirical formulas such as $\frac{D}{d} = 5$, and consideration of the effect of different ore shapes and friction. It was also shown that before determination of digging a Dogleg section, its effect on ore flow should be considered; otherwise it could create a very severe hang-up.

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