©2000, CIVIL-COMP Ltd., Edinburgh, Scotland
B.H.V. Topping, (Editor),
Finite Elements: Techniques and Developments,
Civil-Comp Press, Edinburgh, 207-211.

COMPUTER SIMULATION OF GRAVITY FLOW OF ORE IN ORE PASSES BY THE DISCRETE ELEMENT METHOD (DEM)

H. Nazeri†, G.G.W. Mustoe‡, T. Rozgonyi† and M. Miyata*
†Mining Engineering Department, ‡Division of Engineering
Colorado School of Mines, Golden, Colorado, United States of America
***Port and Harbour Research Institute, Structural Engineering Division**
Ministry of Transport, Yokosuka, Japan

Abstract

Ore passes are vertical or steeply inclined openings in a rock mass through which ore and waste are transported from one mining level to another using the driving force of gravity and where they may also be stored. An ore pass is, in effect, a silo excavated in a rock formation. Production in most deep underground mines depends on the safe and continuous operation of the ore pass system. Since ore passes are dependent upon only gravity for moving the materials, they require less energy. However, despite the existence of standard design guidelines, hang ups, wall failures and other ore pass problems still occur frequently in underground mines. This paper describes the development and application of a rigid cluster and a superquadric based discrete element computer code to predict material flow in ore passes and improve safety and performance. The discrete element method (DEM) model parameters include the size distribution, friction, and shape of ore particles and ore pass geometry.

1. Introduction

Mining has been described as an exercise in bulk materials handling where men and equipment produce ore. In this context an ore pass is an element in the handling system, which also comprise of: stopes, chutes, a crusher, ore bins, loading pockets and the mine shaft. Figure 1 shows a typical ore pass in a mine.

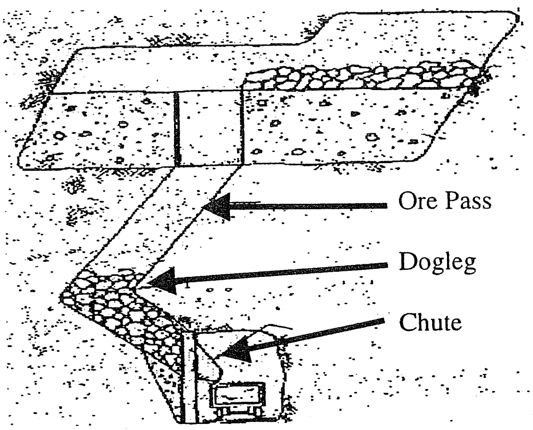

Figure 1 Ore pass system, with a dogleg in an underground mine

A major concern in the design of an ore pass is the prevention of a hang up. The bulk ore consists of particles with different size and shape material, they are usually wet or damp, and often contains clays too. As a consequence, blockage of materials or hang up can frequently occur. Two major types of hang ups should be considered:

a) Hang ups caused by large-sized boulders becoming wedged together to form an interlocking arches. This occurs when the relatively few larger fragments form stable arch arrangements in the ore pass, and
b) Cementation effect of fine and sticky particles that create a cohesive arch type of hang up. Presence of moisture in the bulk ore mass will also increase cohesive resistance of arches within the ore material.

For further information describing safety and design issues involving ore passes, see references [1], [2] and [3].

2. Ore Pass Modeling

Rigid Cluster DEM Model

Because of the irregular shape of ore materials, specialized DEMs for analyzing systems of general shaped bodies are required. At the Colorado School of Mines we have developed a rigid cluster based DEM computer model called cluster2d for ore pass analysis. Note, similar cluster based numerical models have also been developed using a discontinuous deformation analysis (DDA) approach [4,] and in a DEM environment by Itasca Corp. who developed the computer codes PFC2D and PFC3D [5].

The shape of the ore particles are modeled with clusters of rigid overlapping circular disks. For example, Figure 2, shows a particle with an approximate elliptical shape modeled with a cluster of five overlapping circular disks.

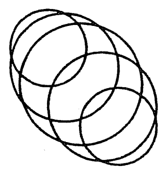

Figure 2 An elliptical particle modeled with a cluster of five overlapping disks

The size distribution of ore material is represented by varying the sizes of the clusters as defined by a specified size distribution function, see Figure 3.

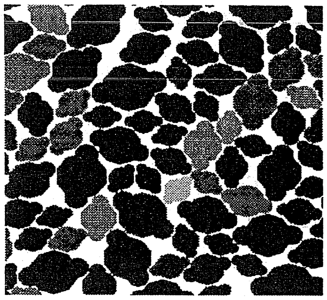

Figure 3 Cluster Shape and Size Distribution

The cluster modeling approach is particularly efficient for material flow of general shaped bodies since the contact checking is the same as for a simple circular disk based DEM model. The only significant change in the rigid cluster algorithm is that the mass and moment of inertia have to be computed carefully taking into account the overlapping cluster disk geometry. The computational method then follows the standard DEM algorithm which contains a i) an automatic contact detection algorithm involving a series of sorting actions and geometry checks of increasing complexity, ii) a contact force generation algorithm that can either compute total force or incremental force updates, and iii) a time integration procedure which is explicit involving a two step generalized velocity and position update. For general details of the DEM, see the conference proceedings [6] and [7].

Superquadric DEM Model

A second DEM model called super2d employing a smooth analytical superquadric representation for non-circular shaped ore particles has also been developed and applied to ore pass modeling. In the superquadric DEM the boundary geometry for a body "i" is defined with respect to local centroidal coordinates by:

$$f_i(x_i, y_i) \equiv \left(\frac{|x_i|}{a_i}\right)^{n_i} + \left(\frac{|y_i|}{b_i}\right)^{n_i} - 1$$

where the point $P(x_i,y_i)$ is: i) outside the body when $f_i(x_i,y_i) > 0$, ii) inside the body when $f_i(x_i,y_i) < 0$ and iii) on the surface when $f_i(x_i,y_i) = 0$. Using a superquadric formulation, non-circular shaped bodies ranging from ellpitical to rectangular shapes can be modeled. For further details of the superquadric DEM model, see Mustoe, Miyata and Nakagawa [8].

3. Ore Pass Simulations

In this section we illustrate the application of the cluster2d and super2d codes to ore pass modeling. These simulations are currently being used to predict a) the flow of material through the ore pass, and b) the dynamic and static loads and stresses on the side walls and the bottom gate/feeder in the ore pass. The DEM simulations of the gravity flow of ore materials in ore passes are summarized below:

i) Loads and stresses in an ore pass filled with circular and cluster shaped ore material

An ore pass which is inclined at 70^0 to the horizontal direction, 4m. wide and 30 m. high, is loaded with ore particles to a height H, is shown in Figure 4.

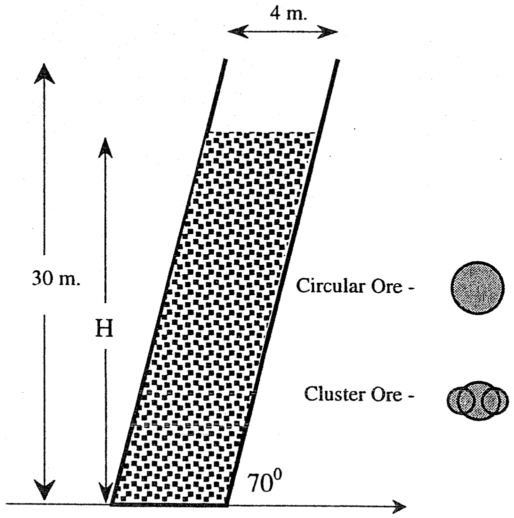

Figure 4 Inclined Ore Pass Geometry and Ore Particle Geometry

The rigid cluster DEM is used to study the static stresses and loading on the ore pass system for different shaped ore.

In the first analysis the ore particles are assumed to be monosized and circular, and in the second analysis the ore particles are monosized and consist of rigid clusters of three overlapping particles, see Figure 4. The mass of a cluster and a circular shaped ore particle is defined to be equal. The number of clusters (and circular particles) in the ore pass is approximately 5500 and the height of the ore material after settling is approximately H = 24 m. Figure 5 shows the average stress distribution in the ore pass filled with cluster shaped particles.

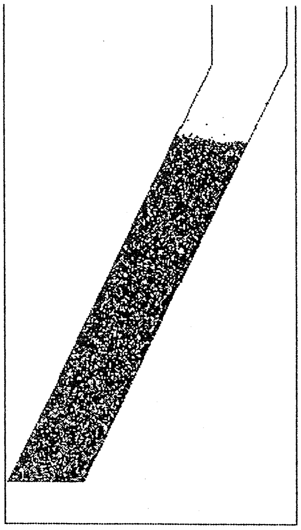

Figure 5 Average Stresses in Ore Pass

The impact factors for the analyses of cluster and circular shaped ore particles are shown in Figures 6 and 7 respectively. Note, the impact factor is defined as a non-dimensional force normalized by the total weight of the ore material.

The results shown in Figures 6a and 7a clearly indicate that the normal forces acting on the inclined walls of the ore pass are significantly higher for circular shaped ore than for the cluster shape ore material. Figures 6b and 7b show that the shear forces acting on the inclined walls of the ore pass are significantly higher for cluster shaped ore than for the circular shape ore material.

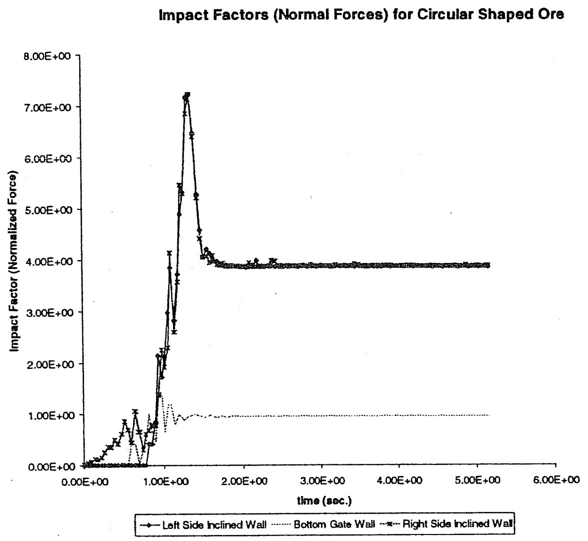

Figure 6a Normal Force Impact Factors for Circular Shaped Ore

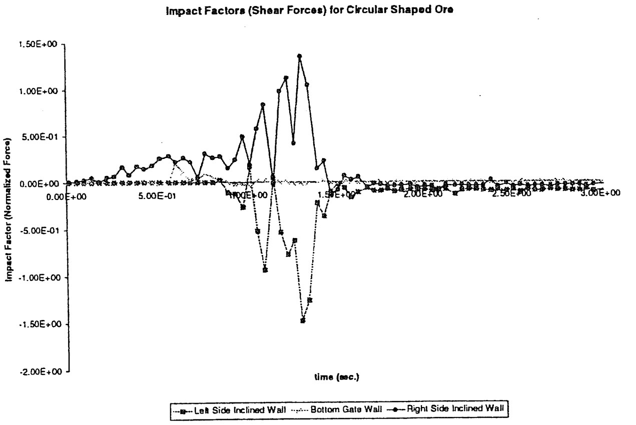

Figure 6b Shear Force Impact Factors for Circular Shaped Ore

Note, the increased shear forces acting on the inclined walls of the ore pass for cluster shaped ore are generated because the cluster shaped ore material forms more stable arches across the span of the ore pass than the circular ore material.

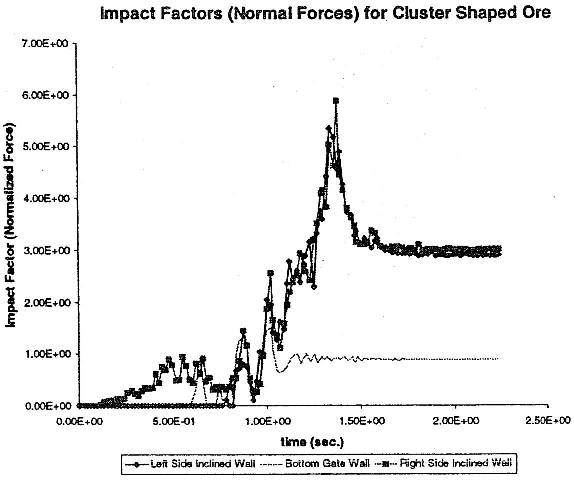

Figure 7a Normal Force Impact Factors for Circular Shaped Ore

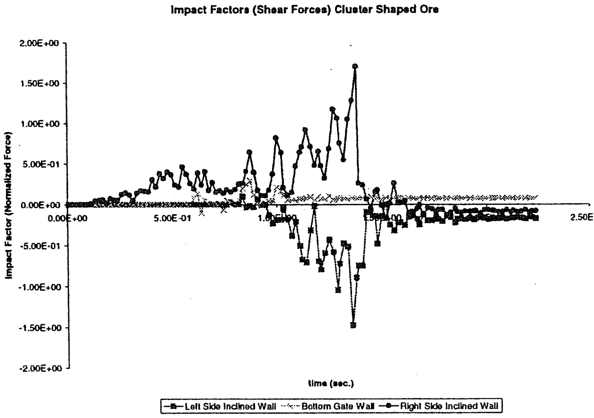

Figure 7b Shear Force Impact Factors for Cluster Shaped Ore

A comparison of the normal stresses acting on an inclined wall of the ore pass for circular and cluster shaped ore is given in Figure 8. This figure indicates that the increase in normal stresses with depth (measured from the surface of of the ore material) is much more pronounced for the circular shaped ore than for the cluster shaped ore. Note, the increase in normal stresses for cluster shaped ore is very gradual after a depth of about 10 m. This is further evidence that the cluster shaped ore form more stable arches across the span of the ore pass than the circular ore material.

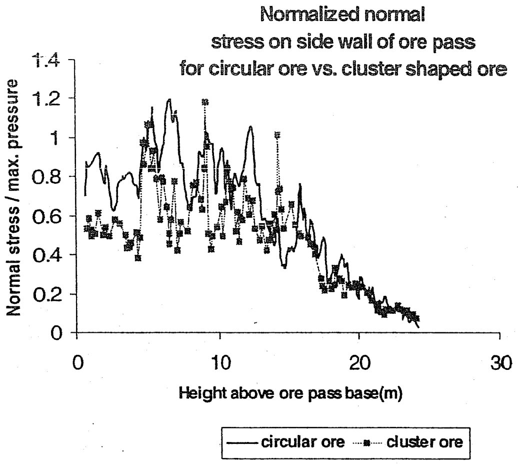

Figure 8 Comparison of Normal Stresses acting on an Inclined Wall

) Loads and force chains in an ore pass filled with circular nd superquadric shaped particles

wo further analyses of the 70^0 inclined ore pass previously escribed were performed using the super2d superquadric EM model. Two systems of 1400 ore particles were anayzed: a) a system of circular particles of radius 0.1 m, and b) system of superquadric, nearly square shaped particles 0.2 . long. Note, the superquadric parameters defining the nearly quare shaped particles were a = b = 0.1 m., and n = 4. Note, hat in these two simulations the system of ore particles was eleased from a height of 35 m. above the base of the ore pass.

igures 9a and 9b show a comparison of the impact factors for ormal forces acting on the inclined walls of the ore pass. The arge maximum values of the impact factors of approximately , seen in these figures are a consequence of the the system of re particles being initially released from 35 m. above the base f the ore pass. Note, that the static impact factor for the recangular ore is approximately 3 and the static impact factor for he circular ore is approximately 2. This difference in impact actors is entirely because of the ore shape.

comparison of the force chains for the rectangular and cirular shaped ore systems is shown in Figure 10. This figure hows that the force chains in the rectangular and circular haped ore systems are significantly different. It may also be nferred that the forces chains in the rectangular shaped ore ystem usually generate more stable arches than in the system f circular shaped ore particles.

ii) Effect of a dogleg in an ore pass

igure 11 shows two simulations of an ore pass with a dogleg ection. In the first analysis the ore particles are assumed to be monosized and circular, and in the second analysis the ore articles are monosized and consist of rigid clusters of three verlapping particles. Note that the masses of the individual re particles in both analyses are the same. Figure 11a shows hat the circular particles flow freely through the ore pass vhereas the cluster shaped particles hang up, see Figure 11b. further analysis was also performed to try and remove the ang up by dumping more ore particles into the top of the ore ass. The result was unsuccessful and the hang up remained.

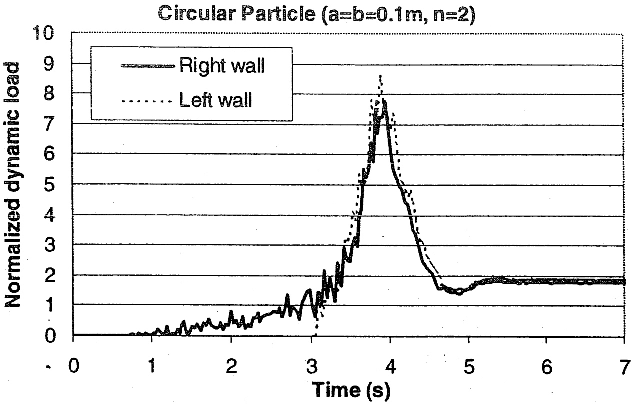

Figure 9a Impact Factors (Normal Forces) for Circular Ore acting on Inclined Walls

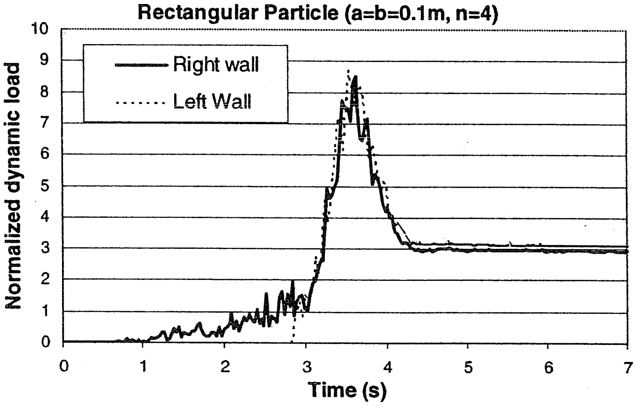

Figure 9b Impact Factors (Normal Forces) for Rectangular Shaped Ore acting on Incined Walls

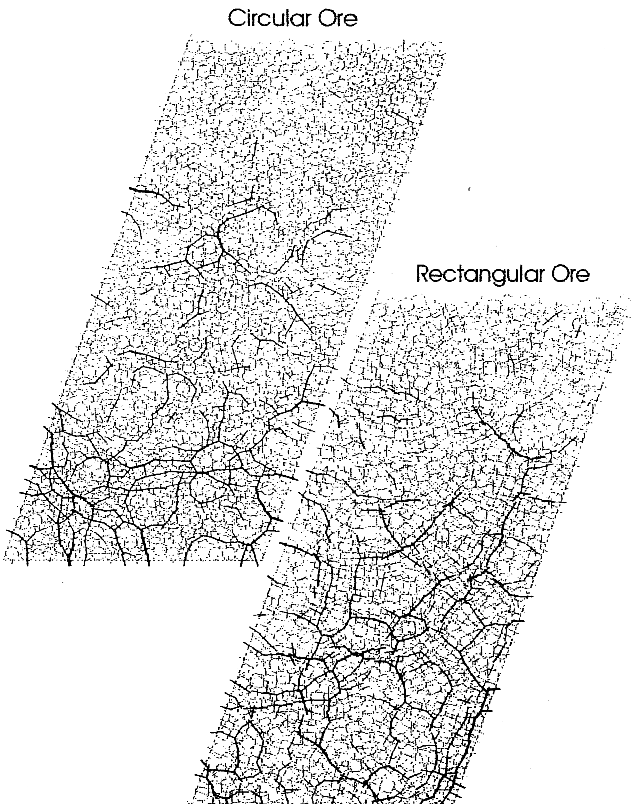

Figure 10 Force chains after settlement

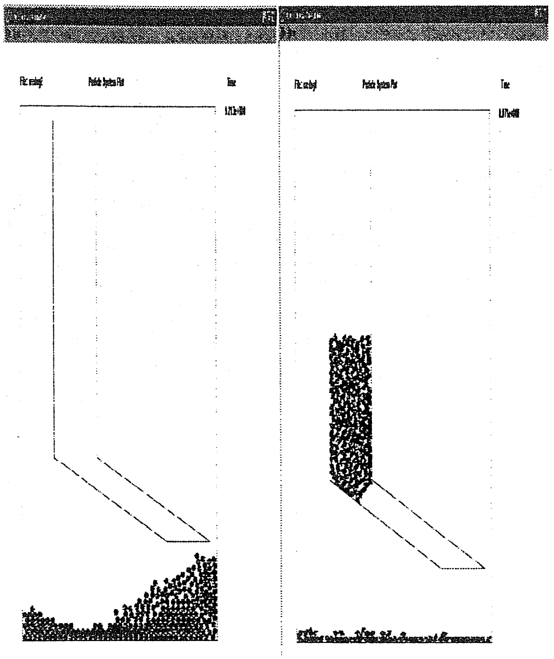

Figure 11 Ore Pass with Dogleg
a) Circular shaped ore particles flowing through an ore pass with a dogleg.
b) Cluster shaped ore particles hung up in an ore pass with a dogleg.

6 Concluding Remarks

The development and application of a rigid cluster and a superquadric based discrete element computer code to predict loads, stresses and material flow in ore passes has been described. The ultimate goal of this research is provide analysis tools that can be used to improve the overall design of ore passes in mines and increase their operational performance and safety.

Three examples were given to illustrate the applicability of these two DEM techniques to engineering analysis of ore passes. The results presented highlight the importance of modeling the shape of the ore particles in the ore pass. In particular it was shown that the loading and stresses acting on the inclined walls and bottom gate of an inclined ore pass are strongly dependent on ore particle shape. It was also shown that the material flow in ore passes with a dogleg section is significantly influenced by ore particle shape. In the third example, a system of cluster shaped ore particles hungup in the dogleg section of an ore pass, whereas a system of circular shaped system of ore particles flowed freely through the ore pass.

Acknowledgements

The authors acknowledge that this work was partially supported through the Western Mining Resource Center (WMRC) in the Mining Department at the Colorado School of Mines funded by the National Institute of Occupational Safety and Health (NIOSH).

The fourth author (MM) would also like to acknowledge the support from the Study Fellowship Program through the Science and Technology Agency of Japan and Dr. Takahiro Sugano of the Port and Harbour Research Institute of Japan.

References

[1]. Peele R. (ed.), " Mining Engineers Handbook. John Wiley & Sons, NY, Third edition, Vol. 1, pp. 10-403, 1941.

[2]. Hambley D. F. "Design of ore pass systems for underground mines" CIM Bulletin, Vol. 80, Jan., pp. 25-30, 1987.

[3]. Stewart B., Iverson S. and Beus M. " Safety considerations for transport of ore and waste in underground ore passes" Mining Engineering, March 1999.

[4]. Thomas P. A. and Bray J. D. " Capturing nonspherical shape of granular media with disk clusters" Journal of Geotechnical and Geoenvironmental Engineering pp. 169-178, 1999.

[5] PFC2D and PFC3D Particle Flow Code Computer Documentation Manuals, Itasca Corp, Minneapolis, MN., USA.

[6]. Proceedings of the 1st U.S. Conference on Discrete Element Methods (Mustoe G.G.W., Henriksen M. and. Huttelmaier H-P, Eds.), Golden, Colorado, USA, 1989.

[7]. Proceedings of the 2nd.. Int. Conf. on Discrete Element Methods, (Williams J.R. and Mustoe G.G.W., Eds.), MIT Press, Boston, MA., USA, 1993.

[8]. Mustoe G.G.W., Miyata M. and Nakagawa M., "Discrete Element Methods for Mechanical Analysis of Systems of General Shaped Bodies", (Submitted to the 5th International Conference on Computational Structures Technology, Leuven, Belgium, September 2000).