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СЪДЪРЖАНИЕ

IMPLEMENTATION OF DISCRETE ELEMENT METHOD TO EVALUATE THE DESIGN AND MATERIAL FLOW IN ORE PASS SYSTEMS

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ABSTRACT
Ore pass systems are one of the main parts of the material transfer process in every underground mine. The extensive literature survey from field investigations connected with the problem of ore pass systems, shows failures and disappointment in the design criteria. The particular concern in the design process of the ore pass systems is the hang-up of materials and the degradation on the ore pass walls generated from impact loads from the material flowing through the finger raise.
In this paper, Discrete Element Method (DEM) of material flow through different ore pass system configurations is being developed and simulated. The purpose of this analysis is to examine the influence of different configuration angles between the ore pass and the finger raise aiming to develop strategies to minimize the hang-up and ore pass wall damage. To suite the define purposes, 9 different DEM models was simulated in order to present methodology that can serve to test and improve the design of the ore pass systems.
The result clearly demonstrated that in the absence of universal guidelines and calculations the DEM analysis is an effective tool for improving and testing the design of the ore pass systems which is unique for every underground mine.
Keywords: *Ore pass, finger raise, system, DEM, analysis, underground mine*

1. INTRODUCTION

Ore passes are vertical or steeply inclined openings in rock mass, and are used to transfer ore or waste material from a higher to a lower level in an underground mine [1]. When the ore pass is evolving to the greater depths and intersects two or more production levels in the underground mine, finger raises are employed to funnel material into the ore pass [2]. Properly design ore pass systems can significantly decrease hauling costs which means that the profitability of a mining operation is strongly influenced by these material handling systems. Typical ore pass system is shown on Figure 1.

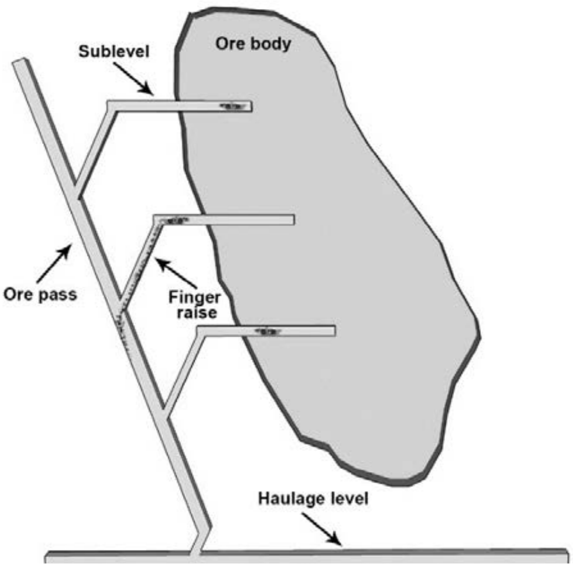

Figure 1. Simplified layout of typical ore pass system in underground mine

The extensive search of literature, indicate that ore pass systems are often associated with a series of operational problems in terms of structural degradation of the ore pass, and problems including hang-up of materials [3-6]. The use of numerical methods allows complex analysis of the factors that can represent the mechanical response of a rock mass and the material flow inside the ore pass system [7].

Esmaieli and Hadjigeorgiou (2011) [8], presented results obtained from numerical experiments based on Particle Flow Code aiming to develop strategies to minimize ore pass wall damage. The degradation of ore pass wall is most often manifested in the expansion of the original dimensions of an ore pass which can significantly influence the stability of the ore pass system. Hadjigeorgiou et al. (2005) [9], reported that cavity survey indicated that in some cases the degradation of the ore pass may expand to close to 20 times that of the original ore pass diameter.

Hadjigeorgiou and Lessard (2007) [3], used the DEM in order to investigate the influence of ore pass geometry, rock fragments shape and size distribution on material flow in an ore pass. The inclination of the ore pass system is closely related to the velocity of material flow which plays a major role in the structural integrity of this material handling systems. Therefore, in the process of designing the ore pass systems a compromise solution must be found between the flow of material and the velocity of impact. In steeper ore pass the material travels faster which can cause more damage on the ore pass walls, on the other hand, the shallow ore pass sections may restrict flow of the material which promotes hang-ups.

Ore pass systems can be kept full and discharge materials at certain times or can be operated as free flow. Infrastructure needed at the discharge point of an ore pass including control chains, chute and etc., are used to control the flow of material. Iverson et al. (2003) [10], used 2D computer modeling to compare dynamic forces at the bottom end of a chute with various ore pass angles and the results are used to improve ore pass design.

On-site investigations in underground mines by Hadjigeorgiou et al. (2005) [9] proved that finger raise often results in a localized impact zone in the immediate vicinity of the ore pass and finger raise junctions.

Literature review failed to provide guidelines for selecting optimal angles of intersection between the ore pass and the finger raise. Most of the reviewed studies implement 2D DEM to investigate some configurations of the ore pass systems in order to improve the overall design. This study will focus on the implementation of 3D DEM to evaluate the material flow between finger rise and ore pass which in the text are referred to the term ore pass system. The main factors that will be followed in the process of designing an improved ore pass system are minimizing the possibility for degradation in the intersections and eliminating the occurrence of hang-ups from the material flow.

2. METHODS

2.1. Configuration of ore pass system

Ore pass configuration including length, shape, diameter, inclination and implementation of finger raise are important factors in selection of design and ore flow [11]. Gravity-induced rock flow in ore pass systems can result in the development of wear or impact damage zones. The design configuration of the ore pass system is very important for extending the life of this material handling systems.

The length of an ore pass section is generally dictated by the ore pass excavation method and usually depends from the vertical distance between mine levels or sublevels. The development of long ore pass sections have a greater probability of intersecting geological zones of poor ground which can pose more operational problems. Also the use of longer sections requires the development of finger raises on several sub levels to funnel material into the ore pass [12].

The shape of ore pass systems is usually associated with the development method where circular ore pass sections are excavated using raise boring methods, while rectangular sections are excavated using Alimak methods.

The most used guideline about the minimum cross section dimension of an ore pass is from the research done by Stacey & Swart (1997) [13]. In in their study the minimum cross section dimension of an ore pass (D) compared to the maximum size of rock fragment to be handled (d), is set to ($3<D/d<5$), to avoid the possibility of hang-ups and blockages.

Inclination of the ore pass has direct effect on the material flow and is dictated by the need to accelerate or decelerate the gravity-induced rock flow. In steeper ore pass sections the material flow increases velocity, which can cause more damage, degradation rate on the ore pass walls and impact loading in the bottom of the ore pass. Shallow inclination on the ore pass sections does not facilitate required material flow, especially if the flowing materials are fine materials. To accomplish a balance between the free and fast flow of ore and a reduction of dynamic load, the ore pass system can be designed with a dogleg section, which is an abrupt change in the bottom inclination of ore pass (Figure 3).
The literature review point to the fact that DEM analysis is the best method and also the cheapest to evaluate and test the design of the ore pass system. This research examines the influence of different ore pass system configurations aiming to develop strategies to minimize hang-ups and wall degradation based on simulated DEM analyses. The proposed methodology for testing the ore pass system configurations is shown on Figure 2.

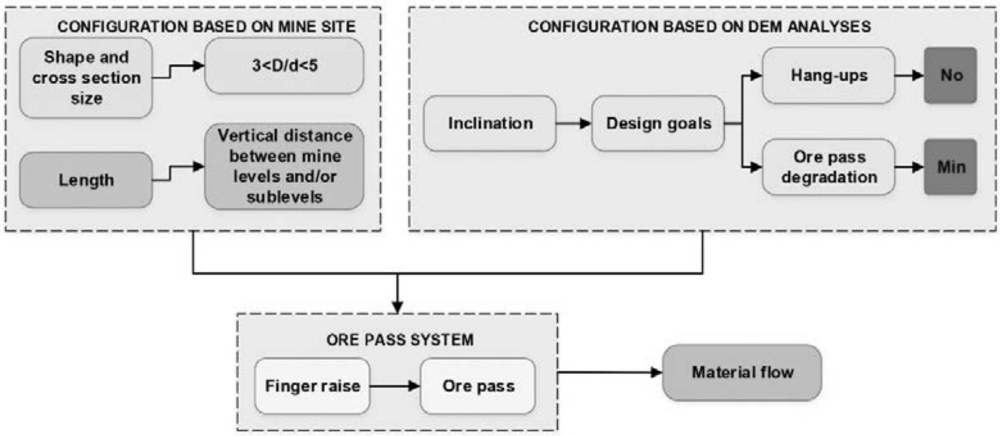

Figure 2. Flow chart for the implementation of the methodology for testing the ore pass system configurations

2.2. Model formulation

A 3D model was developed to replicate the ore pass system in underground mine, as shown in Figure 3. The model was explored by running of numerical experiments using the open-source software Yade, powered by DEM for bulk material simulation. The DEM is a numerical method which predicts the motion of individual and independently moving particles. The working principle and the equations behind the DEM can be found in [14,15].

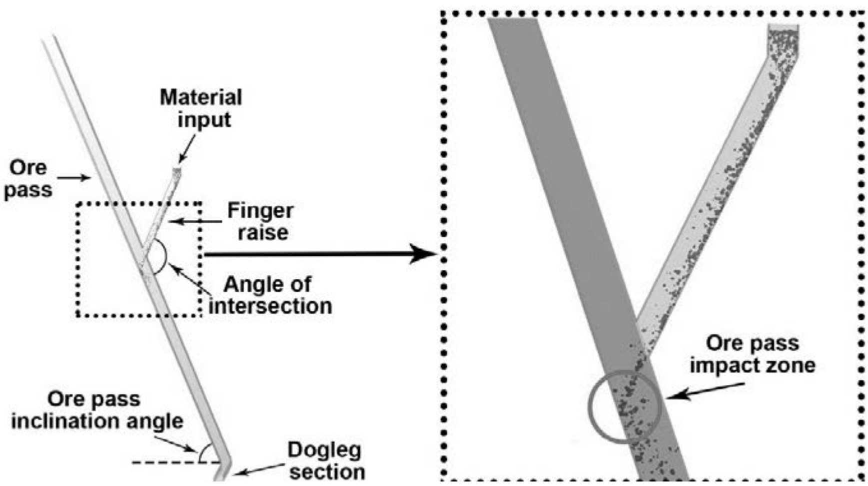

Figure 3. 3D model of ore pass system used in the DEM analyses

The mechanical and physical properties of rock fragments (material flow) in the DEM model include: particle shape, density, material size distribution, material angle of repose, shear stiffness, rolling friction coefficient, static friction and coefficient of restitution. The input data for the dimensions of the ore pass system and the mechanical and physical properties of rock fragments are based on hypothetical underground mine for lead and zinc. The geometric and material properties of the ore pass system used in this work are summarized in Table 1.

Table 1. Geometric and material properties used in the DEM models

Property	**Value**
Ore pass length	80 [m]
Ore pass cross section	2 m x 2 m = 4 [m^2]
Ore pass inclination angle	Variable (70°,75°,80°)
Finger raise	15 [m]
Finger raise cross section	1.5 m x 1.5 m = 2.25 [m^2]
Finger raise angle of intersection	Variable (135°,140°,145°)
Particle material density (rock fragments-lead and zinc ore)	3200 [kg/m^3]
Material density of the ore pass system	3000 [kg/m^3]
Material angle of repose	45°
Shear modulus	1.0×10^7 [Pa]
Coefficient of restitution for particles	0.5
Coefficient of static friction for particles	0.7
Coefficient of rolling friction	0.15
Particle size (radius)	0.02-0.4 [m]

For the purposes of this paper, a total of 9 simulations are made using the Yade open-source software. The simulations consist of three different ore pass inclinations (70°,75°,80°) connected with three different finger raise inclinations and for each of them a separate DEM analysis has been made in which the intersection angle of the finger raise is set in three 5 degrees' increments (135°,140°,145°). The configuration of the DEM models for ore pass and finger raise with the resulting angles of inclination and intersection are summarized in Table 2.

Table 2. Ore pass and finger raise DEM models configurations based on inclination and intersection angles

	DEM model 1	**DEM model 2**	**DEM model 3**	**DEM model 4**	**DEM model 5**	**DEM model 6**	**DEM model 7**	**DEM model 8**	**DEM model 9**
Ore pass inclination angle (°)	70	70	70	75	75	75	80	80	80
Finger raise angle of intersection (°)	145	140	135	145	140	135	145	140	135

The 3D CAD model was first created for each of the ore pass systems and imported into the Yade open-source software. The next step is to enter the geometric and material properties with the previously defined inclination and intersection angles summarized in Table 1 and 2.

After the material properties were defined, it was decided to model cluster out of three spheres to provide a more realistic approach of the material and also to limit the potential to roll freely like the single sphere does. The cluster out of three spheres is shown on Figure 4. In this study, the particles contained in the material are

dry and free flowing where the normal contact force is calculated from the Hertz-Mindlin (no slip) theory. The details of these models calculated from the Hertz-Mindlin (no slip) theory are available hire [15].
The next step is to define the amount of generated material which for the purposes of this paper is taken to be equal to the unloading of one typical scoop bucket size of 2.5 m^3. If we assume that the scoop bucket is 70% full the amount of material is 6944 kg. In real situation the size distribution of the material loaded in the ore pass system will depend on the drill and blast parameters in the stopes which is not the scope of this research. Because of this it was decided to set the size distribution of the material to have normal distribution with values of mean=0.5 and standard deviation = 0.3.

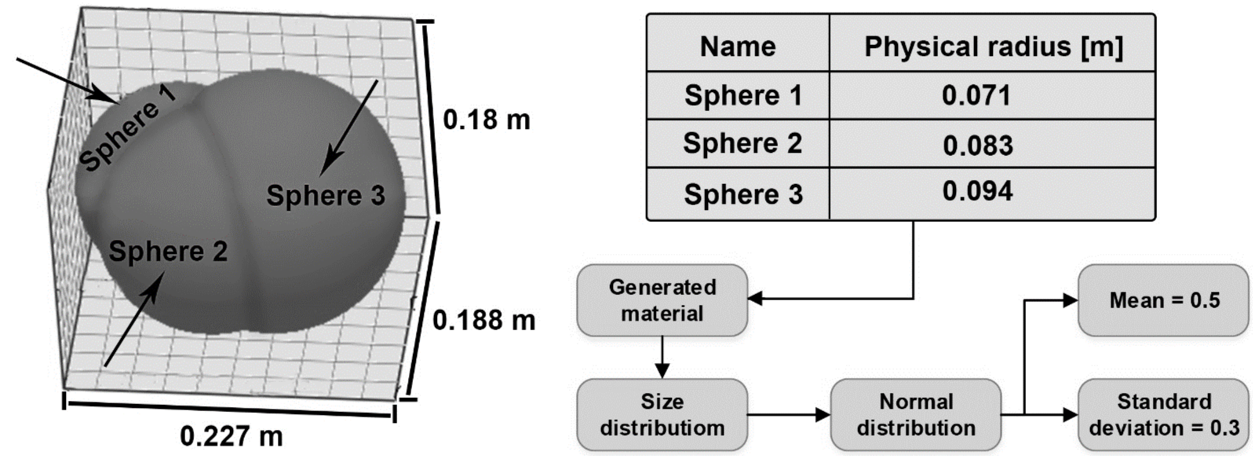

Figure 4. Process of modeling the material flow in the ore pass system

Based on the previously defined parameters an injection plane in the finger raise was developed from where one bucket of material will be passed through the ore pass system and the results from each of the simulations will be analyzed.

3. RESULTS AND DISCUSSION

DEM analyses with Yade open-source software was used to simulate the effects of material flow on different ore pass system configurations whit special focus on examine the design configuration of this material handling systems.
In the undertaken DEM simulations, the ore pass system dimensions was kept constant (Table 1) except the inclination and intersection angles of the ore pass and the finger raise (Table 2). The maximum fragment size in the material flow was 0.4 to ensure that flow is maintained and there are no hang-ups in the ore pass based on the D/d ratio of ore pass dimension per maximum rock block size (Figure 2). In order to simplify the model presented in this paper, we will not consider or measure the effects on material passing through the grizzly and the dynamic loads from the material on the chute at the bottom.
To reproduce the closest simulation of material flow possible we used particles created in random odd shapes (cluster of 3 spheres).
Once the particles were generated in the top section of the finger raise, they start to flow and collide with other particles and with the walls prior to entering the ore pass and striking the facing wall (Figure 3).
During this process the particles have different velocity profiles because of the assigned friction values to the particles and the walls of the ore pass system.
The velocity flow profile of material flow in this papers is set by measuring the average velocity of group of particles at the same time interval on a measurement box right before hitting the ore pass wall. The velocity flow profile of the material flow dumped into the different ore pass system configurations (Table 2) are shown on Figures 5, 6 and 7.

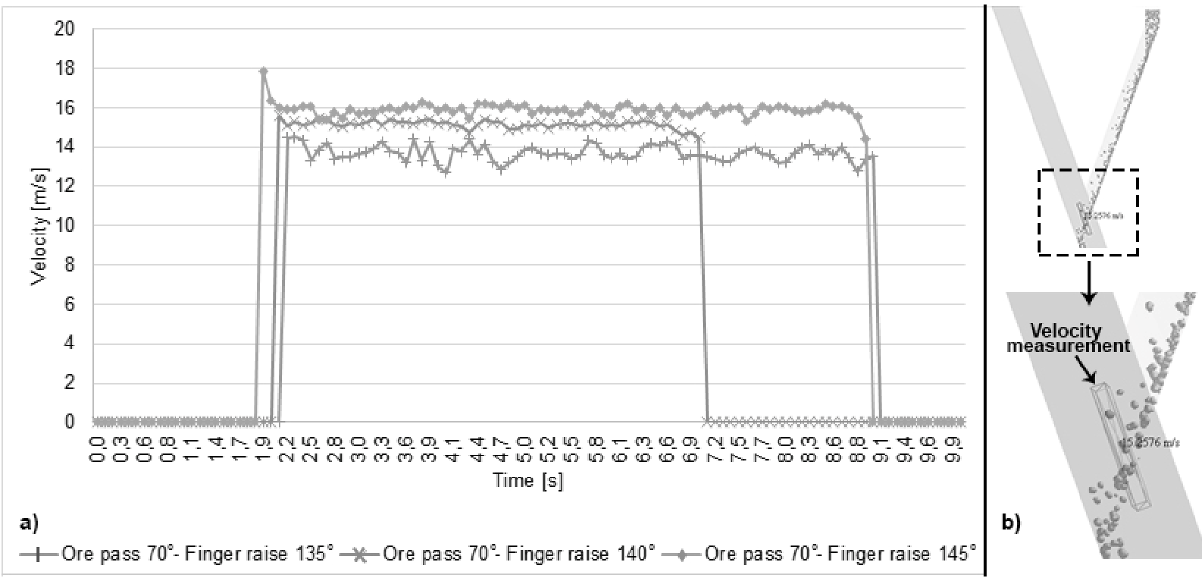

Figure 5. Material flow velocity through ore pass with 70° inclination and intersection angle of the finger raise in three 5 degrees' increments (135°,140°,145°) b) position of the velocity measurement box

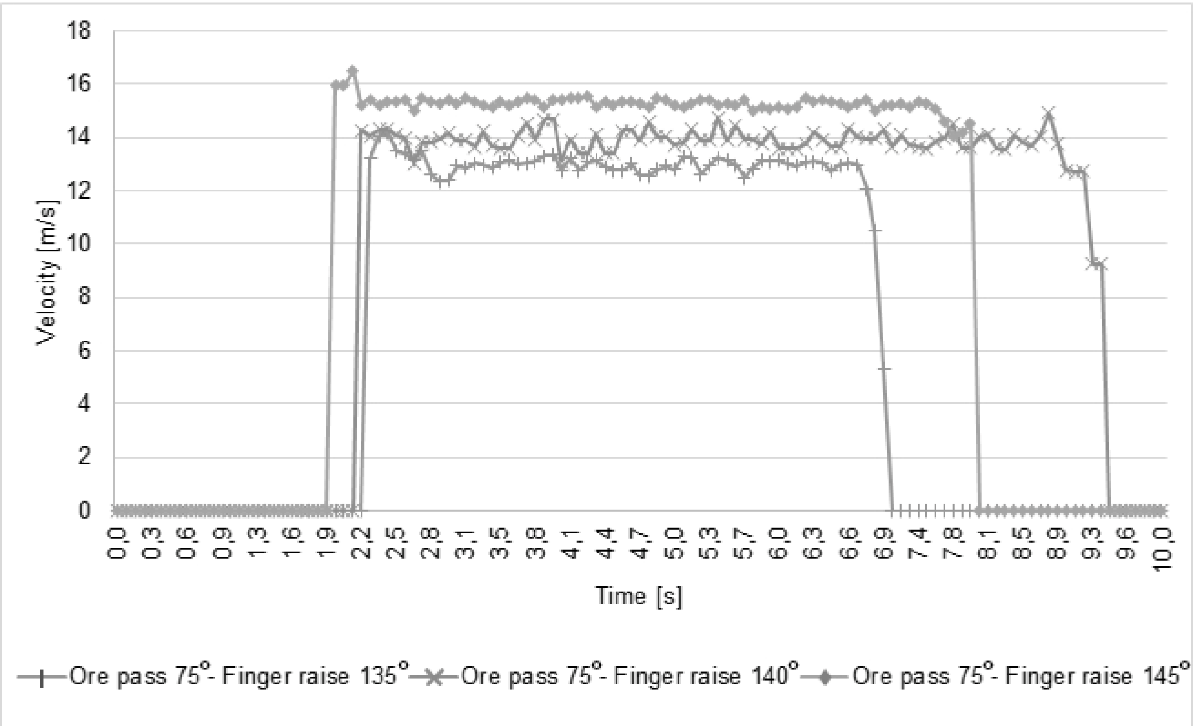

Figure 6. Material flow velocity through ore pass with 75° inclination and intersection angle of the finger raise in three 5 degrees' increments (135°,140°,145°)

The velocity of the material flow travelling through the finger raise depends on the mass of the particle and the forces acting between particle-wall and also particle-particle collisions. The particles that are in front of the material flow have the least interactions between particle-particle and therefore have a significantly higher velocity, which can be concluded from the presented results. The maximum velocity which the material flow will achieve is right before it impacts the ore pass wall. From the analysis of the results shown on Figure 5, 6 and 7, an obvious conclusion can be drawn that by increasing the intersection angle between the ore pass and the finger raise there is an increase in the velocity of material flow through the finger raise. Accordingly, by increasing the inclination of the ore pass, there is a significant reduction in the velocity of material flow through the finger raise, because by changing this angle, the slope of the finger raise changes correspondingly. Due to the randomness in the process of generating particles we have a different unloading time of the total amount of material for each scenario, so because of this in the presented results the time of material flow through finger raise can not be compared.

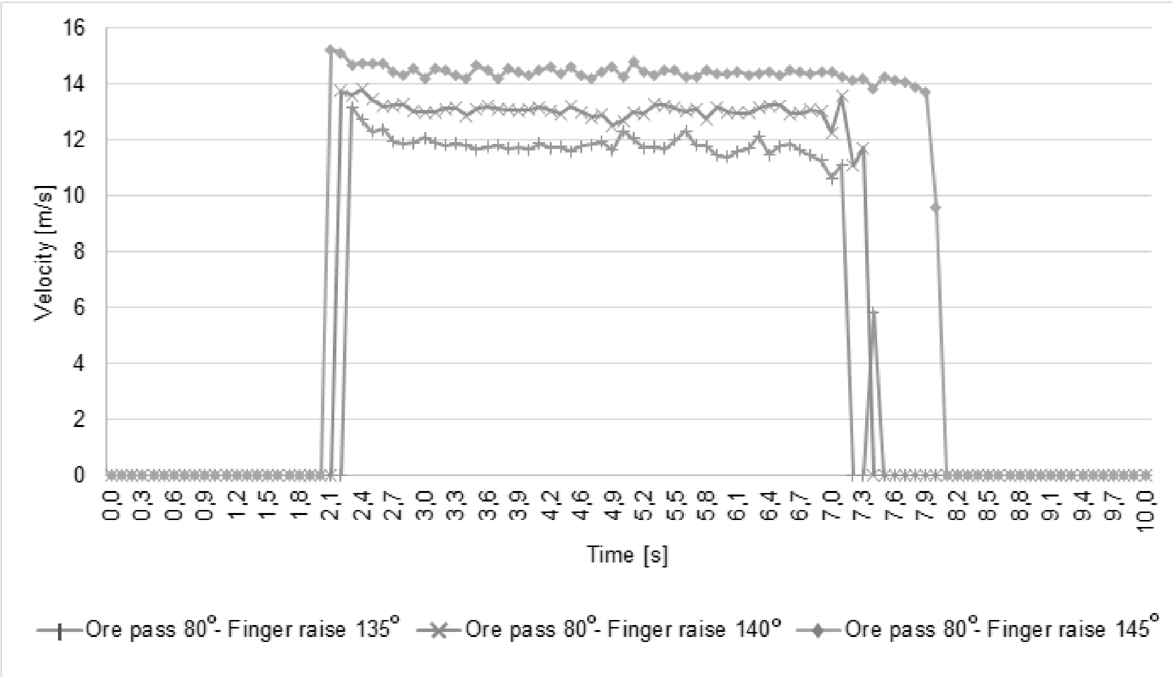

Figure 7. Material flow velocity through ore pass with 80° inclination and intersection angle of the finger raise in three 5 degrees' increments (135°,140°,145°)

Figure 8, 9 and 10, compares the kinetic energy of the material flow right before hitting the ore pass wall for the same ore pass system configurations.

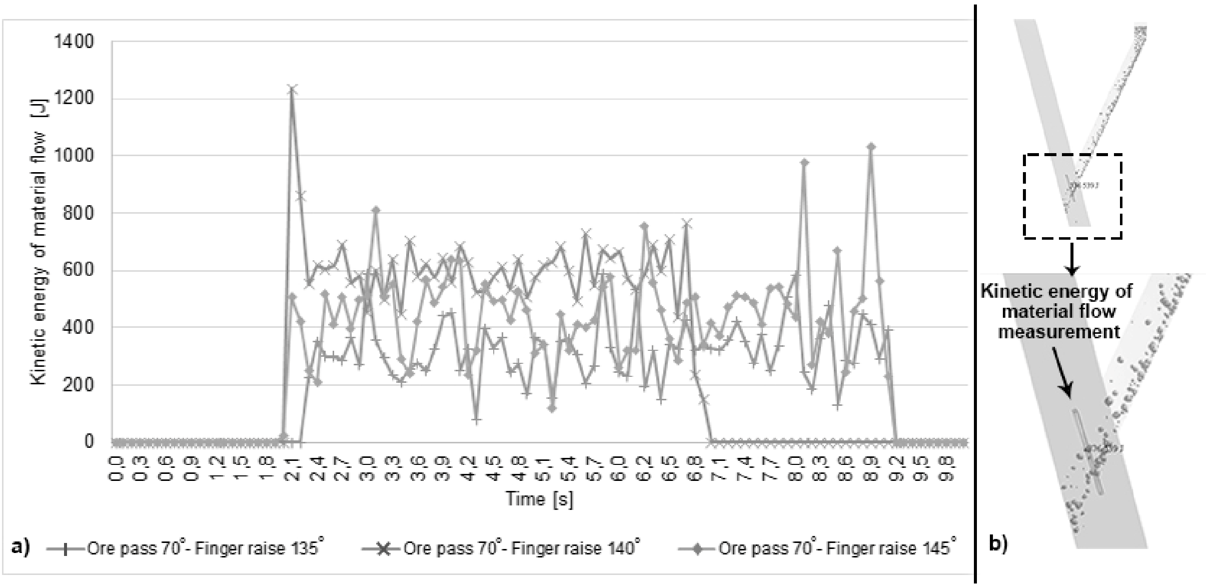

Figure 8. Kinetic energy of material flow through ore pass with 70° inclination and intersection angle of the finger raise in three 5 degrees' increments (135°,140°,145°) b) position of the kinetic energy measurement box

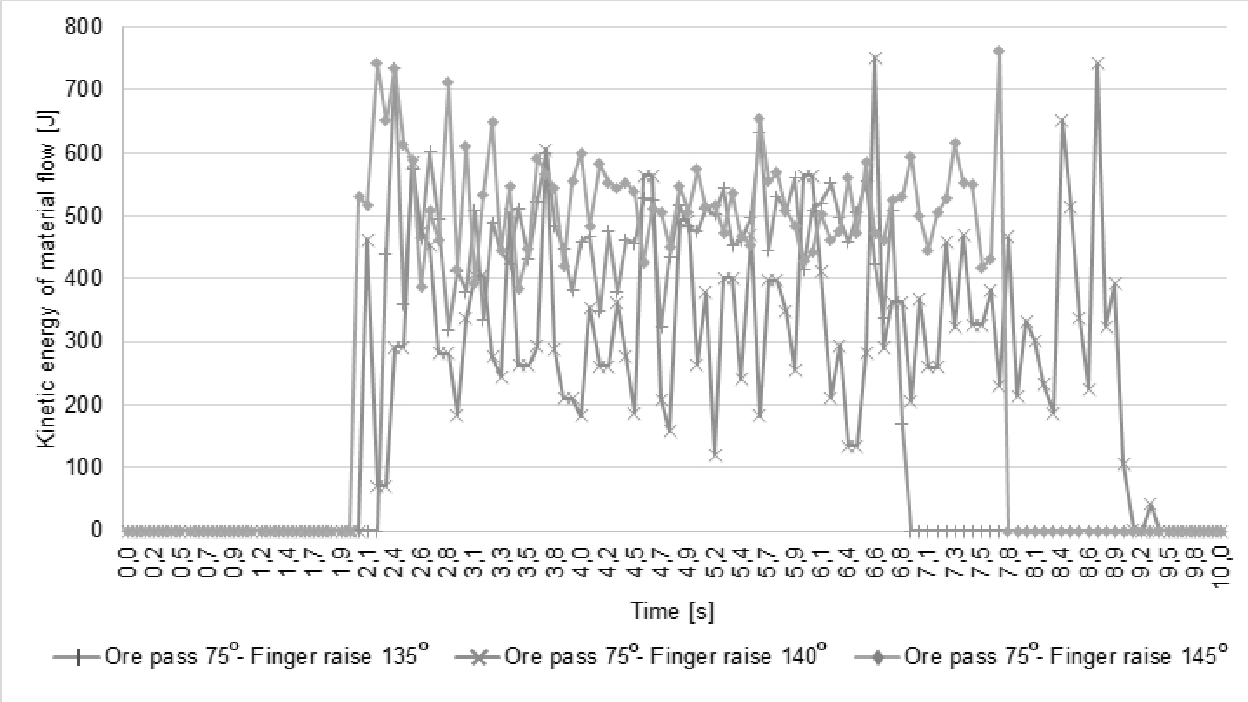

Figure 9. Kinetic energy of material flow through ore pass with 75° inclination and intersection angle of the finger raise in three 5 degrees' increments (135°,140°,145°)

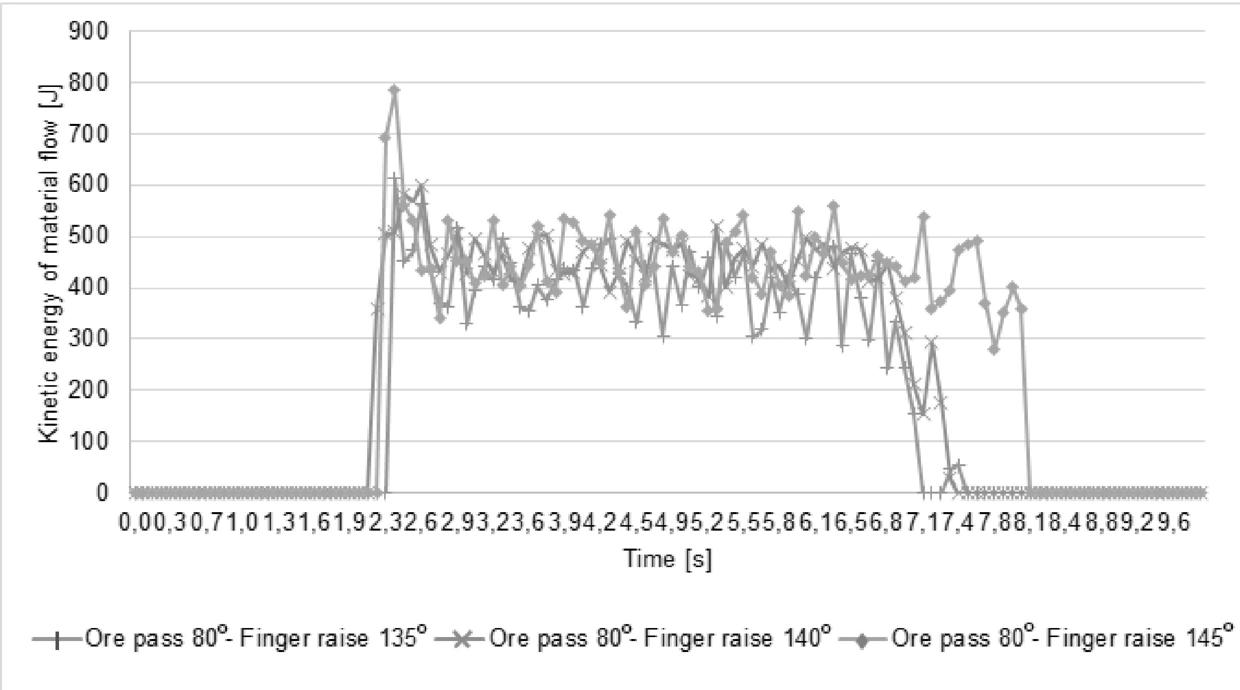

Figure 10. Kinetic energy of material flow through ore pass with 80° inclination and intersection angle of the finger raise in three 5 degrees' increments (135°,140°,145°)

The kinetic energy of an individual particle at the impact zone on the ore pass increases with higher acceleration of the particles. This is an obvious conclusion, but raises the question for the optimal connection between the ore pass and the finger raise in order to ensure less degradation in the impact zone without the possibility of creating hang-ups of materials.

The kinetic energy of material flow in this papers is set by measuring the average impact of group of particles at the same time interval on a measurement box right before hitting the ore pass wall.
From the presented results on Figure 8, 9 and 10, it can be concluded that the magnitude of the material flow kinetic energy is highly dependent on the velocity, mass and number of particles that will simultaneously hit the ore pass wall. By increasing the unloading time of the material in the finger raise can significantly reduce the particles that will simultaneously hit the ore pass wall.
Due to the use of the previously mentioned material properties and the configuration angles between the ore pass and the finger raise, none of the presented scenarios show signs of material hang-ups in the ore pass system.

4. CONCLUSION AND FUTURE ASPECTS

DEM analysis to assess the design of ore pass system have been evaluated. The ore pass system in this study is based on hypothetical underground mine for lead and zinc, in which 9 scenarios were simulated and the results are used to examine the material flow parameters. The results from the analyses emphasizes the influence of the ore pass inclination angle with the corresponding intersection angle of the finger raise on the resulting velocity and kinetic energy of material flow from which the degradation of the ore pass walls and hang-ups of material depends.
The methodology presented in this study provides opportunities to test multiple variations of the ore pass system with geometries and configurations that are unique and different for each underground mine. Due to the lack of guidelines and calculations that can be used to improve the ore pass system design and also to reduce the walls degradation, the methodology presented in this paper is a unique solution to this problem.
Future work will include extension of the research to measure the resulting impact from the material flow on the ore pass walls by coupling the DEM analysis with computational fluid dynamics (CFD) analysis.
Opportunities for further research also exists in including the grizzly and the chute system in consideration for the process of improving the ore pass system.
Also foundations for future work exists in building a prototype system for controlling the unloading time of the material in the finger raise in order to reduce the particles that can simultaneously hit the ore pass wall. This prototype system must take into account the fact that the calculated optimal time will not have an impact on reducing the efficiency of the loader, the ore pass system and the overall mine as a whole.
The methodology in this paper was presented for demonstration of applicability of DEM techniques that will hopefully contribute to the process of improving the ore pass system design which is unique for every underground mine.

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