Influence of finger configuration on degradation of ore pass walls

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ABSTRACT: This paper addresses issues associated with ore pass degradation caused by material impact. A series of numerical experiments, using the particle flow code, were undertaken to investigate the influence of various finger raise configuration. This has allowed the identification of favorable configurations. The results of this analysis, when coupled with field observations, can contribute to the design of ore pass systems that can prolong the useful operating life of ore pass systems.

1 INTRODUCTION

Material transfer in underground mines often relies on the use of ore pass systems. Fragmented ore is transported from stopes, or production faces, to a tipping point where it is dumped into the ore pass. When an ore pass intersects two or more production levels finger raises are employed to funnel material into the ore pass. In this configuration, material flows into the finger raise and falls into the ore pass at the junction between the ore pass and finger raise. Material is subsequently drawn out from the ore pass using a chute system.

Hadjigeorgiou et al. (2005), Lessard & Hadjigeorgiou (2006), Stacey & Swart (1997) report that finger raises are often associated with operational problems. The drop of rock fragments results in high impact loads acting on the walls of an ore pass that can contribute to the degradation of the ore pass system. This can result in enlargement of the area where a finger raise intersects the ore pass, Figure 1. This phenomenon has been confirmed by cavity monitoring surveys at several mine sites, Lessard & Hadjigeorgiou (2006).

The extent of inflicted damage by impact loading of the ore pass walls, is influenced by the type of material transferred, finger and ore pass configuration, and the rock mass quality of the walls. The material characteristics that are more critical are particle shape, hardness, density and size distribution. On the other hand, the capacity of ore pass walls to resist impact loads is influenced by the rock mass characteristics and the in situ stress regime. It is recognized that the presence of structural defects in the rock mass results in more pronounced wall degradation.

This paper presents a series of numerical experiments, using the distinct element method (DEM), in particular the particle flow code (PFC) to simulate the influence of ore pass and finger configuration on impact loading of the ore pass walls. It investigates the magnitude of impact loads generated by rock fragments on the ore pass walls for a range of ore pass and finger configurations.

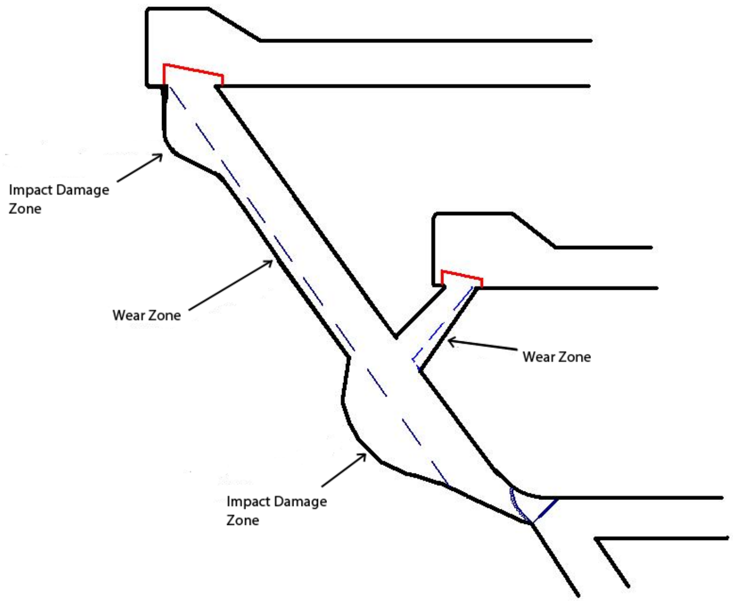

Figure 1. Damage zones in an ore pass.

2 ORE PASS DEGRADATION DUE TO IMPACT

In ore pass systems gravity movement of rock includes rolling, sliding and inter fragment collision. The interaction of moving material and ore pass walls can result in the development of wear and/or impact damage zones. Wear is associated with the particles rolling and sliding along a surface resulting in the scouring of the wall surface. Damage attributed to impact loads can be caused by single falling boulders in the ore pass, a stream of rock or a large mass of material, Iverson et al. (2003). The mechanical properties of the rock mass along the ore pass wall can influence the extent of damage. Stacey & Swart (1997) note that wear of ore pass walls is greater in weak rock material and in the presence of stress scaling. If the ore pass is located in a rock mass with structural defects the action of moving material can initiate further wall degradation, including falls of ground.

Ore pass wall damage, induced by impact, is one of the most important mechanisms of ore pass degradation. This paper reports on-going work, using numerical models, on the influence of material impact for several ore pass and finger raise configurations.

3 FINGER RAISE CONFIGURATION

Figure 2 illustrates a typical finger raise - ore pass configuration. Hadjigeorgiou et al. (2005) report that, in Canadian underground mines, finger raises have cross section dimensions of 1.5 m x 1.5 m and 1.8 m x 1.8 m. The fingers are linked to ore passes of larger cross section dimensions.

A well designed finger raise can minimize the ore pass wall damage and maximize ore pass longevity. Current practice is often based on empirical rules which quite general and may not always be appropriate for site specific conditions. Empirical guidelines provided by Hambley et al. (1983) and Ferguson (1991) recommended an inclination of 60^{o} for finger raises in order to ensure free flow of rock fragments in the finger raise. This recommendation, however, does not seem to be respected in several mines where we observe a range of finger inclinations.

The finger raise inclination influences the motion and interaction of rock fragments flowing in the ore pass and the resulting load on the ore pass wall. If the finger raises are steep this will result in higher impact velocity on the ore pass walls. On the other hand if the finger inclination is shallow material flow is slow and can result in hang-ups. A steeply inclined finger raise results in narrower pillars at the intersection of the ore pass and finger raise which are more susceptible to stability problems. Consequently an operational design will use a finger raise inclination that will minimize impact load on the ore pass wall while maintaining material flow in the finger.

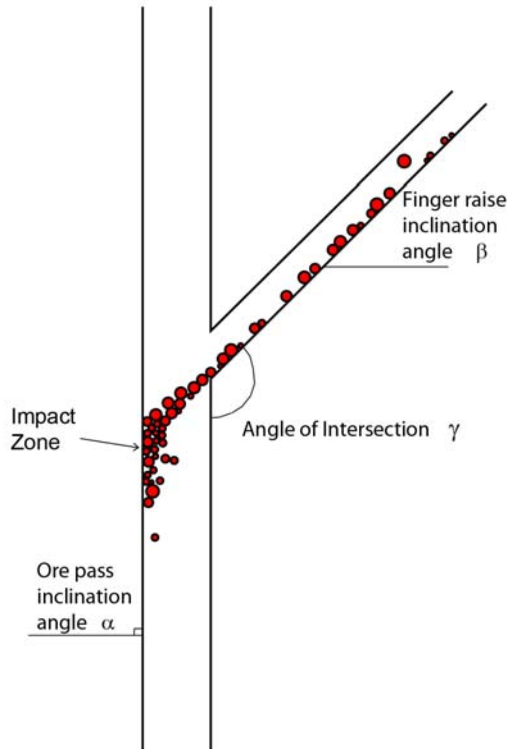

Figure 2. A typical configuration of a finger raise.

4 IMPACT LOAD SIMULATIONS

Material transport in an ore pass using distinct element models, and in particular the particle flow code (PFC) by Itasca (2008) has been investigated by several authors, including Lessard & Hadjigeorgiou (2003). This was justified given that the flow of granular material exhibit large-scale discontinuous dynamic behavior which is not well represented by conventional continuum-based approaches like the finite element methods. The distinct element method was also employed by Iverson et al. (2003), Nazeri & Rozgonyi (2003), Loughran et al. (2003) to evaluate the impact of rock fragments on several ore pass components.

This study also used the particle flow code to model the movement and interaction of particles that represent rock boulders or fragments. In order to construct representative models we relied on information on material properties collected in several Quebec underground mines, Lessard & Hadjigeorgiou (2003). Several ore pass and finger raise configurations were selected to quantify the influence finger raise inclination on the resulting impact loads on the ore pass wall.

4.1 *Simulation of rock fragments and wall properties*

The physical and mechanical properties of rock fragments simulated in the PFC2D model include: rock size distribution, particle shape, normal and shear stiffness, density, friction coefficient and coefficient of restitution. The main source of input data for the numerical models was provided by Lessard & Hadjigeorgiou (2003) and Turcotte (2004) where they described the methodology to derive suitable material properties for PFC ore pass models. The material properties used in the context of the present work are summarized in Table 1.

Table 1. Material properties used in the PFC models.

Property	Particles	Ore pass wall
Density	4300 kg/m^3	-
Normal stiffness	1.0×10^9 N/m	1.0×10^9 N/m
Shear stiffness	1.0×10^9 N/m	1.0×10^9 N/m
Friction Coefficient	0.25	0.4
Particle size (radius)	0.12m – 0.4 m	-
Coefficient of restitution	0.3	-

Larson et al. (1998) simulated material flow in an ore pass using a single particle moving in an ore pass. Although this provides a reasonable estimate of the resulting impact on the walls it cannot account for collision between particles. Inter particle collisions can result in smaller loads applied on the ore pass wall.

Particle size distribution in an ore pass has been simulated by using a unique average particle size, Beus et al. (1998) or by generation of particle size distributions, Iverson et al. (2003). Although this provides for more comprehensive models it comes at the expense of the model complexity and time of execution. Nazeri (2001) and Lessard & Hadjigeorgiou (2003) used uniform size distributions, assuming good blasting practice, and a maximum size deviation of 15% for their numerical models. The smallest particle size in the generated distribution was assigned a value of 30% of the largest particle. Lessard & Hadjigeorgiou (2003) determined the size of the largest rock fragment in an ore pass based on the grizzly dimensions installed at the tipping point. In the absence of grizzlies the largest particle size was estimated as d_{90} based on visual estimations and in certain cases image analysis from data collected in Quebec underground mines

Blasted rock, results in fragments of various shapes. In PFC2D the basic particle shape is circular but it is possible to construct different shapes by grouping circular particles together. For the purposes of the numerical analysis circular rock fragment shapes were used in order to expedite the time necessary to run the models. The normal and shear stiffness of particles reported in Table 1 were based on a series of numerical experiments where the model behavior was calibrated with respect to laboratory and field data. It should be noted that Nazeri (2001) demonstrated that the use of large contact stiffness values results in larger impact forces on the walls of the ore pass. The employed PFC models used a slip-model, defined by a friction coefficient between particles to control their frictional characteristics. Based on previous work the friction coefficient was assigned a value of 0.25. It is recognized that the choice of friction value will influence material flow. The friction forces along with damping forces are responsible for a significant of loss in kinetic energy of gravity flow of ore.

In order to be able to simulate collision between particles it is necessary to establish appropriate values for the coefficient of restitution (COR) of rock fragments. Jung & Iverson (2004) have addressed this issue and have noted that there are several acceptable definitions of COR. In the present work we defined the Coefficient of Restitution as the ratio between the magnitudes of the rebounding and impacting velocities.

The coefficient of restitution can be measured by both laboratory and in-situ tests. In situ tests will provide values for the coefficient of restitution that take account of rock fractures and surface conditions as well as the rock material types. However these tests are very expensive and may not be practical. Rock drop test is the most popular test that can be done in both laboratory Chau et al. (2002), Imre et al. (2008) and in field scale, Azzoni & de Freitas (1995). This test can be easily simulated with numerical methods. The test is based on the initial height of the object before it was allowed to fall and the height of bounce after the impact. The COR for this test can be written as follow:

$$m \times g \times h_i = E_i = \frac{1}{2}(m \times V_i^2)$$

$$COR_V = \frac{V_r}{V_i}$$

$$COR_V = (\frac{h_r}{h_i})^{0.5}$$

Where m is the particle mass, V_i and V_r are the incoming and rebounding particle velocities, h_i is the initial height of the particle before it was allowed to fall and h_r is the height of bounce after the impact.

The coefficient of restitution of rock fragments falling or sliding along a surface depends on a variety of factors including size, shape, type of the rock fragments, the geometry of the surface, the velocity of the rock fragments and the impact angle, Azzoni & de Freitas (1995).

In computer models like PFC damping factors are used to simulate the coefficient of restitution of particles. There are several numerical damping methods such as local damping, viscous damping, and hysteretic damping. These are used to maintain numerical stability in PFC when simulating quasi-static processes. Itasca (2008) suggested local damping is inappropriate for particle in free flight under gravity or for impact of particles. When a dynamic simulation of compact assemblies is required, the viscous contact damping should be used.

There is no standard way of determining the coefficient of restitution of rock fragments, particularly in an underground infrastructure like an ore pass. For the purpose of these numerical analyses a coefficient of restitution of 0.3 was assigned to the rock fragments. This is within the range of 0.2 to 0.6 reported by Iverson et al. (2003) based on physical model pendulum tests.
A PFC2D simulation of a single particle drop test on a rock mass with the properties of the ore pass wall was undertaken. In this experiment the viscous damping parameters were varied in order to arrive at the desired 0.3 COR reported in Table 1.

The ore pass walls absorb the dynamic impacts of rock fragments. A rigid wall property was considered for the both ore pass and finger raise simulation. This implies good rock mass quality of the ore pass wall where there is no structural defect. Stiffness and friction coefficient of the walls are listed in Table 1.

4.2 *Simulation of Ore pass and Finger raise Configuration*

A total of 33 ore pass and finger raise configurations were modeled using PFC2D. Three different ore pass inclinations (α = 90°, 80° and 70°) were considered, Figure 3. The inclination of the finger raise (β) ranged from 30° to 80°, at 5° increments. The ore pass inclination (α) and finger raise inclination (β) result in different angles of intersection (γ) as summarized in Table 2.

Table 2. Ore pass and finger raise configurations and resulting angles of intersection.

Ore pass Inclination (α) (°)		Finger raise Inclination angle (β) (°)										
		30	35	40	45	50	55	60	65	70	75	80
Angle of Intersection (γ)(°)	70	100	105	110	115	120	125	130	135	140	145	150
	80	110	115	120	125	130	135	140	145	150	155	160
	90	120	125	130	135	140	145	150	155	160	165	170

In the undertaken simulations the ore pass dimension was 3.5 m and the maximum size of rock fragments was 0.8 m. In order to avoid hang-ups in the ore pass a 3 to 5 ratio of ore pass dimension per maximum rock block size (D/d) is necessary, Hadjigeorgiou & Lessard (2007). The finger raise width was assigned a length of 2 m which is smaller than ore pass dimension.

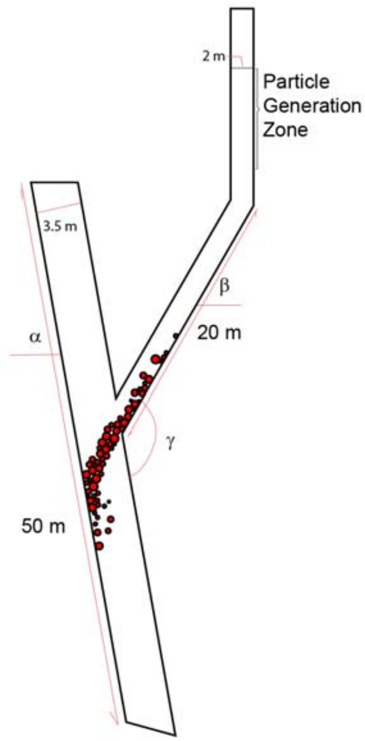

Figure 3. Ore pass and finger raise configurations used in the numerical modeling.

The ore pass was 50 m long and the finger raise was 20 m long. In order to simulate the particles in the finger raise a particle generation zone was constructed in the model. In each numerical experiment only one batch of rock fragments were generated in the particle generation zone. Each batch of particles contains 80 circular particles of varying size ranging from 0.12 to 0.4 m of radius. Assuming that the particle shape can be extrapolated as a sphere the total volume for each generated batch of particles is approximately 5.5 m^3, which corresponds to a typical scoop bucket size, used in Quebec underground mines.

5 ANALYSIS AND INTERPETATION OF RESULTS

Five numerical experiments were performed for each ore pass and finger raise configuration. In all 165 numerical experiments were performed to investigate material flow and the resulting impact loads on the ore pass wall.

The first step in the simulations was the generation of the particles which were introduced into the finger raise. Particles flowing through the finger raise collide with other particles and with the walls of the finger raise before coming into the ore pass and hit the facing ore pass wall. During the simulations the following parameters were monitored: velocity and kinetic energy of particles, impact duration, average normal and shear impact force and peak impact load.

5.1.1 *Influence of finger raise inclination on particle velocity and kinetic energy*

The velocity of particles hitting a rock mass influences the extent of inflicted rock mass damage. Hutchings (1992) reported that the extent of impact wear depends on the number and mass of individual boulders striking the surface, and on their impact velocity. More specific to ore passes, Goodwill et al. (1999) suggest that erosion wear in ore passes is roughly proportional to the impact velocity raised to the power of 2.5.

In the undertaken PFC analysis the motion of selected modeled particle was defined by the resultant force and moment vectors acting upon it. This can be described by the translational and rotational motion of a particle. Consequently the translational velocity of the particle at a given time can be expressed as:

$$V\left(t+\frac{\Delta t}{2}\right)=V\left(t-\frac{\Delta t}{2}\right)+\left(\frac{F(t)}{m}+g\right)\Delta t$$

Where
V is the particle velocity, Δt is a time-step, F is the sum of all externally applied forces acting on the particle, m is the mass of the particle.

As illustrated in Figure 3, particles generated in the generation zone are allowed to drop into the finger raise. Once the particles enter the inclined finger they begin to collide amongst themselves and the floor. The velocity of particles travelling in the finger raise depends on the mass of particle and the external forces acting on the particle via particle-particle or particle-wall collisions. The velocity of particles increases with an increase in finger raise inclination and reaches a maximum at the impact zone on the ore pass wall.

In each numerical experiment, the velocities of two random particles were monitored. Finally for every finger raise and ore pass configuration the average impact velocity was calculated based on the results of five numerical experiments. Figure 4 presents the effect of finger raise inclination on the impact velocity of particles at the ore pass wall for 70°, 80° and 90° ore pass inclinations. For less steep finger raise inclinations, between 30° to 40°, there is no large variation in the impact velocity. However for steeper finger raise inclinations the impact velocity in vertical ore passes is slightly higher. This is due to the longer distance that particles exiting the finger have to travel before they hit the ore pass wall.

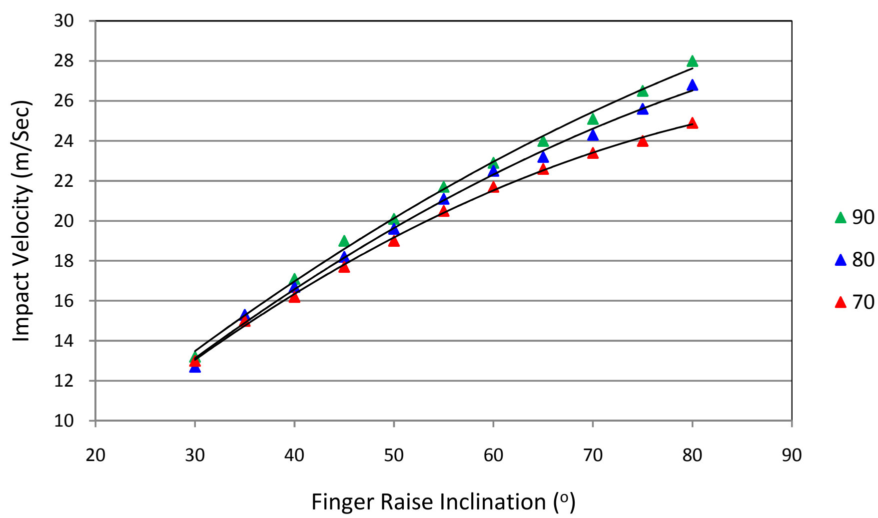

Figure 4. The influences of finger raise inclination on the particle impact velocity; for 70°, 80°, and 90° ore pass inclination.

The energy of rock fragments that enter a finger raise is dissipated by inter particle collisions and along the ore pass walls by falling or sliding of the particle stream. The amount of energy transferred to the walls depends on deformation characteristics of the flowing rock particles and the rock mass along the ore pass wall surface. It is also recognized, although not monitored, that particle impact also generates heat and sound.

In PFC the total kinetic energy of all particles accounting for both translational and rotational motion can be traced. The kinetic energy is defined by:

$$E_k=\frac{1}{2}\sum_{N_b}(m_i^i V_i^2+I_i\omega_i.\omega_i)$$

Where N_b the number of particles, m_i, inertial mass, I_i, inertia tensor, V_i is the translational and ω_i is the rotational velocities of particle i.

Figure 5 illustrates the influence of finger raise inclination on the kinetic energy of particles at the zone of impact. The kinetic energy of particles increases with an increase of finger raise inclination. The increase is more pronounced for the vertical ore passes fed by steep finger raises. This is due to the higher impact velocity of particles for this type of configurations.

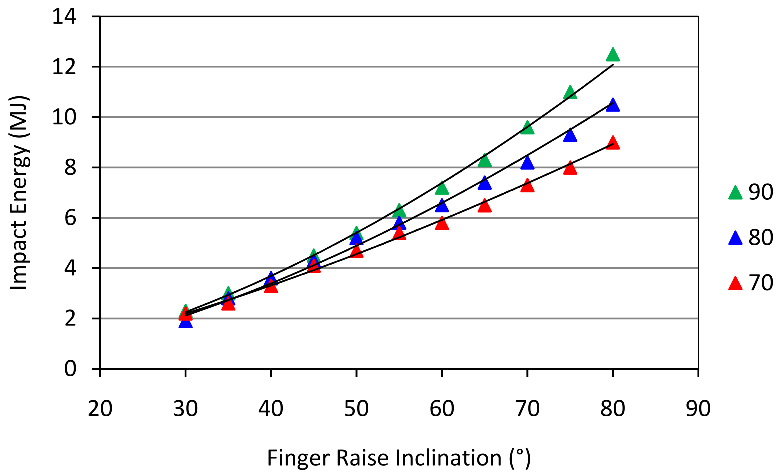

Figure 5. Influence of the finger raise inclination on the kinetic energy of particles.

5.1.2 *Effect of finger raise inclination on impact load of particles on ore pass wall*

Impact duration, the period of time between the first and the last particle impact, was monitored during the numerical experiments. When the impact duration is short this results in a significant impact pressure on the ore pass wall, and consequently more wall damage. The duration of impact on the wall depends on the weight flow rate of particles in the finger raise which in itself is a function of particle velocity.

Impact duration decreases as finger raise inclination increases Figure 6. For a particular finger raise inclination the impact duration for vertical ore passes is shorter, particularly when ore passes are fed by steeper finger raises.

The average normal and shear impact forces on the ore pass wall were measured for all ore pass and finger raise configurations. Figure 7 presents the resulting normal and shear impact forces acting on ore pass walls inclined at 70°, 80° and 90° while the finger raise inclination is kept at 60°. The shear impact force on the ore pass wall increased when the ore pass inclination decreased. In reviewing the results in the format of shear and normal forces might eventually allow for a more thorough investigation of the possible degradation mechanisms and for consideration of the influence of defects in the ore pass wall.

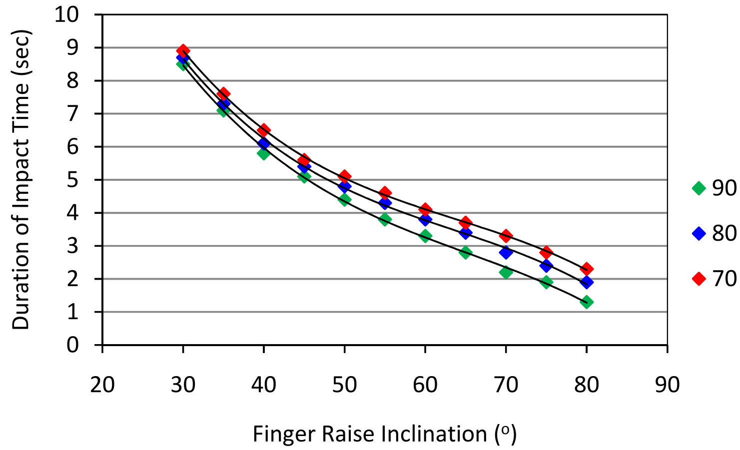

Figure 6. Influence of the finger raise inclination on the impact duration.

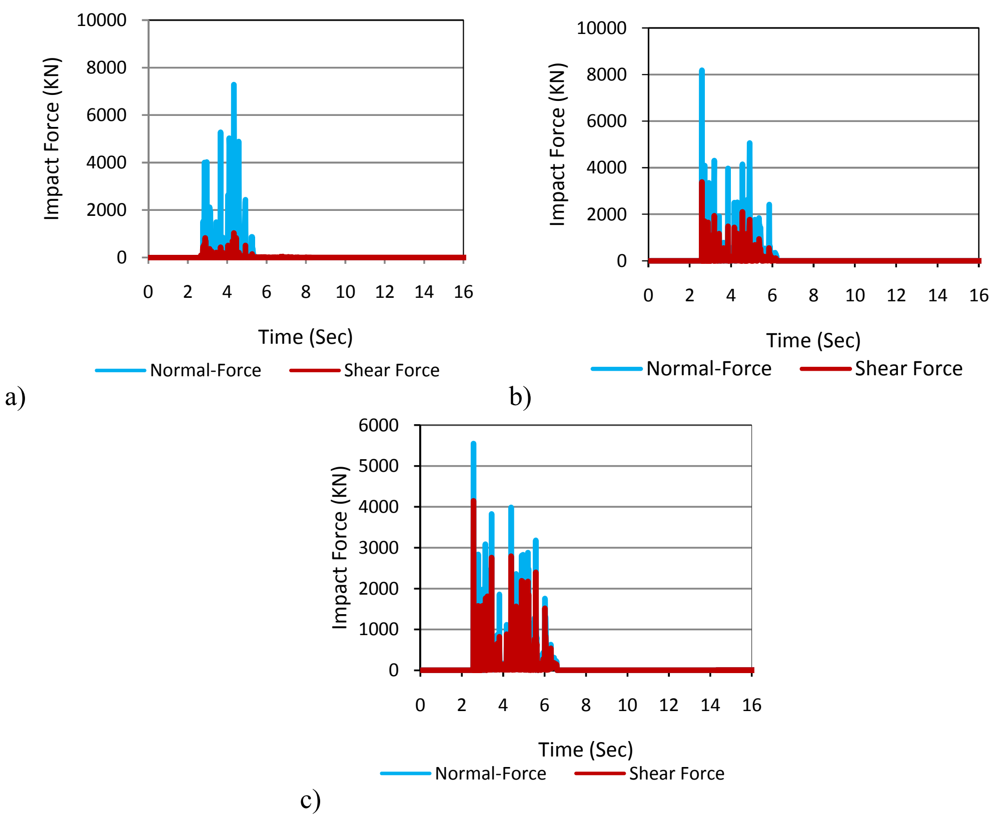

Figure 7. Normal and shear impact forces acting on inclined ore pass walls with the finger raise inclination of 60°; a) Ore pass inclination 90°, b) Ore pass inclination 80° and c) Ore pass inclination 70°.

The influence of finger raise inclination on resulting average shear and normal forces acting on the ore pass walls is illustrated in Figure 8. These results, however, should be interpreted with reference to the angle of intersection (γ) between the raise finger and the ore pass as defined in Figure 2. The highest average forces are recorded for angles of intersection between 140° to145°. For a vertical ore pass maximum impact loads were recorded when the raise finger was inclined close to 55°.

The average normal impact force, for all investigated ore pass inclinations, is between 1200-2000 kN. The average shear impact force increases with a decrease in ore pass inclination. The ratio of average shear impact force to average normal impact force, for vertical, 80° and 70° inclined ore passes is approximately 0.1, 0.4 and 0.8 respectively. An increase of shear impact force can potentially accelerate the rate of degradation at the ore pass wall.

Beus et al. (1999) measured the magnitude of dynamic impact loads from rock fragments on a gate of an ore pass in an underground mine in Idaho. Subsequent PFC3D simulations overestimated by a factor of five the magnitude of dynamic impacts when compared to the field data. This overestimation is probably due to the difficulties in modeling material properties such as particle shape, stiffness, coefficient of restitution and etc. Nevertheless, this approach can provide valuable information in comparing different design options.

The peak impact force of particles acting on the ore pass wall depends on the number of collisions that a particle incurs prior to striking the ore pass wall. The relation between finger raise inclination and the peak impact loads acting on the ore pass walls is shown in Figure 9.

The results of 165 simulations of material entering the ore pass through inclined finger raises were analyzed with reference to the peak impact force acting on the ore pass wall. The worst case scenario, i.e. resulting at high impact loads and consequently likely to result in greater damage on the wall was for intersection angles of 140° and 145°. The maximum impact load was generated for the vertical ore pass at a 55° finger inclination (intersection angle of 145°). Maximum impact loads for the ore pass inclined at 80° was when the finger inclination was 65° (intersection angle 145°) and for an ore pass inclined at 70° and a finger at 70° at an intersection angle of 140°. These results identify an interesting trend that if it is validated by future investigations can have significant implications on the design of raise fingers and ore pass systems.

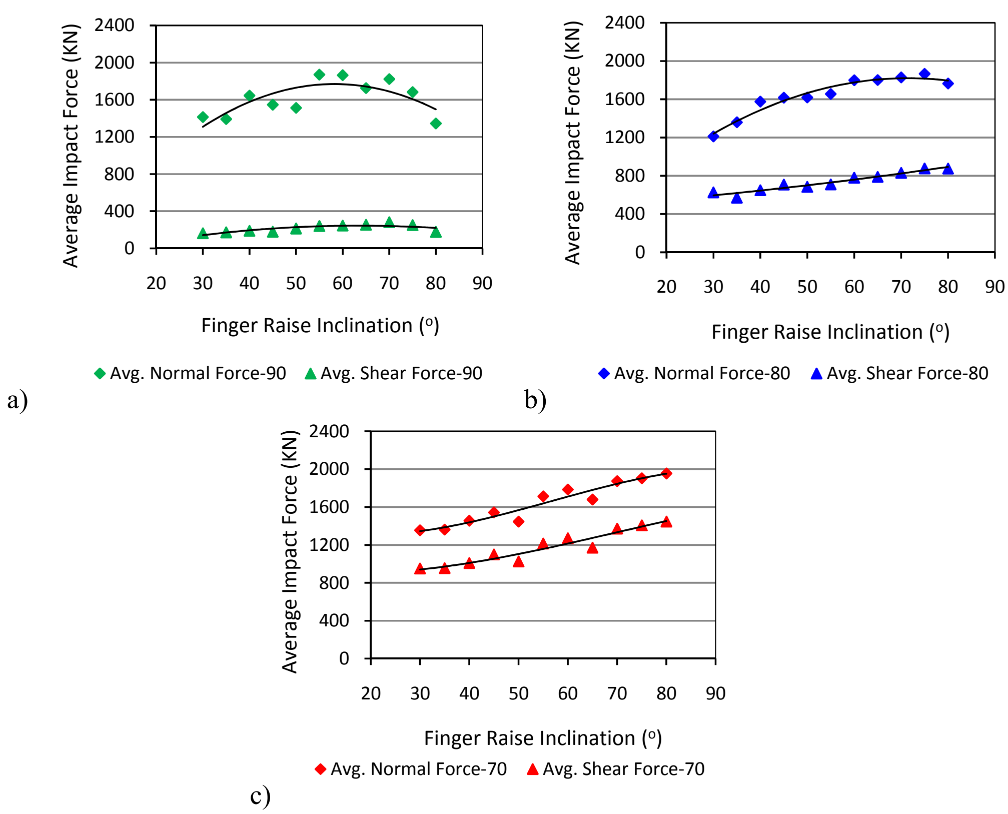

Figure 8. The influence finger raise inclination on the average normal and shear impact forces; a) Vertical ore pass, b) Ore pass inclination 80°, c) Ore pass inclination 70°.

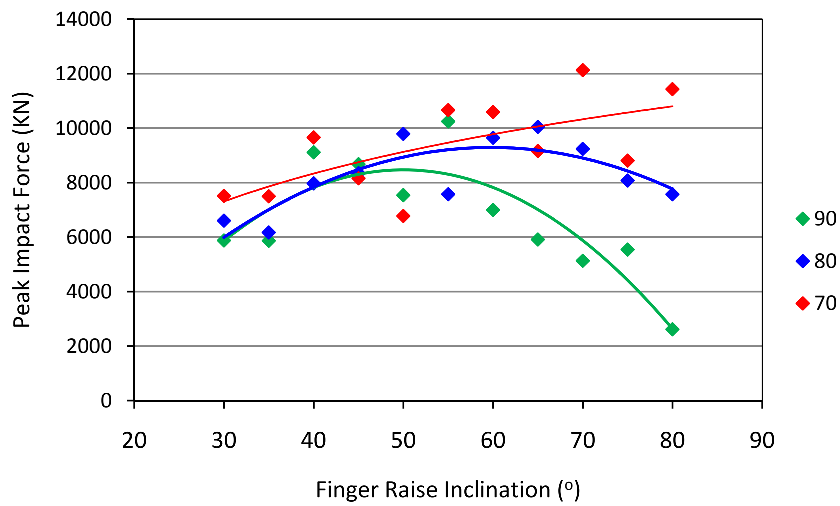

Figure 9. Influence of finger raise inclination on the peak impact load of particles on the ore pass wall.

6 CONCLUSIONS

This paper reports the results of numerical experiments on the influence of ore pass and finger raise configurations on ore pass damage by material impact. Available data from field and numerical studies were used to help construct a series of parametric investigations using the particle flow code. In the numerical investigation material properties were kept constant during 165 runs while the ore pass and finger inclination was allowed to vary. The influence of different configurations on the impact on the ore pass wall has been quantified and presented in the form of charts.

It has been demonstrated that particle impact velocity and kinetic energy increase with finger raise inclination. The impact duration decrease with increase of finger inclination. These observations can be used to evaluate different options of finger inclination for any particular ore pass inclination. In order to compare the influence of both ore pass and finger inclination it is necessary to account for the resulting intersection angle. This consideration does not appear to have been taken into account in current design practice. The results of the undertaken analysis however clearly demonstrate that the choice of intersection angle can have significant influence on the resulting impact loads on the ore pass wall and the location and magnitude of damage to the ore pass. The highest impact loads were reported for intersection angles of 140^{o} and 145^{o}.

7 AKNOWLEDGMENTS

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