Effects of Fragmentation Size Distribution on Truck-Shovel Productivity

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ABSTRACT

Fragmentation size distribution affects shovel productivity through digability and fill factor and truck productivity through payload, loading time and waiting time at the loader. The reviewed models indicated that shovel productivity depends on P_{80} (fragment size at which 80 percent of material passes) and uniformity index. Suggested models are based on post-blasting assessment and since they were prepared for fragmentation distribution, they do not consider all factors influencing productivity such as material looseness, swell and equipment parameters. Since productivity is affected by several factors other than fragmentation distribution, its prediction (establishment) requires more involving models.

Truck-shovel productivity just like other downstream operations (crushing and grinding) are affected by fragmentation distribution which is a product of blasting. A collective approach to increase productivity and lower operations cost should focus on increasing blasting effectiveness. Blasting should be designed to provide a fragmentation size distribution that ensures the efficiency of downstream processes. This can be done by manipulating blasting set up if the target fragmentation is known.

1. Introduction

Fragmentation distribution is an important parameter in productivity of the mine. Blasting is the first stage of fragmentation; its efficiency affects the downstream activities such as loading, crushing, milling and refining. Coarser material lead to higher energy consumption, increased wear rates as well as lowering load and haul productivity and crushing and milling throughputs. Different researches have been conducted on the effects of fragment sizes on downstream operations; this paper is going to review approaches and models established from the studies of fragmentation size distribution effects on truck-shovel productivity and identify research gap. The review aims at improving prediction models to improve the productivity of the mines and minimize operations costs.

The main objective of drilling and blasting in mining is to generate a muck pile with a suitable size distribution of rock fragments that can be handled efficiently on loading, transporting, crushing and milling. Initially, optimum drill and blast designs considered getting the rock to a manageable size for trucks and shovels and minimize both drilling and explosives costs (Singh, R., 2006). With 'Mine to Mill' concept, the focus has shifted whereby blasting practices are modified to achieve energy optimization in all downstream activities. Blasting is now designed to increase load and haul productivity and ensure mill feed size which saves up on energy and increase throughput (McKee, 2013).

Jethro (2016) determined the effects of fragmentation on loading using the Kuz-Ram Model and Split Desktop Software; he observed that with every increase of 10 cm in fragmentation size, loading time increases by 2 seconds. Singh (2006) conducted a study to determine factors affecting the productivity of loading equipment in mines; the conclusion was, bucket fill factor and rate of production decrease with increasing mean particle size and index of uniformity. Tosun, Konak, Karakus, Onur, and Ongen (2012) observed that the increase in pile density (good fragmentation) increases loading efficiency. Doktan (2001) observed increased productivity of 22% for truck shovel system with better fragmentation.

This paper is organized in two sections which are literature review and discussion. Literature review is divided into three parts. The first part defines fragmentation size distribution and different ways used to assess and quantify fragmentation distribution. Effects of fragmentation size on truck-shovel productivity are briefly described. The second part describes characteristics of rock fragments at different size distributions, and through these characteristics, the effects of size distribution on productivity is explained. The third part reviews models describing effects of fragmentation size distribution to truck-shovel productivity. Discussion section, analyses findings from the review and propose future areas of research on fragmentation size aiming at maximizing productivity and minimize overall mine operations costs.

2. Literature review

Truck shovel productivity can be affected by several factors including machine design which define how efficiently the energy is used and mine plan and design relating to dig methods. Others include shovel-truck matching, operator’s skills and practices and operating conditions; rock fragmentation and material digability (Awuah-Offei, 2017). On the other hand, truck productivity depends on the capacity of shovel, operator’s skills, material characteristics (swell factor, density, fragmentation), payload and fill factor, truck size, engine power, drive system, fleet management efficiency and haul roads conditions. The capacity of the truck should not exceed 6 to 8 times shovel bucket capacity and shovel should have appropriate height and reach.

Apart from the load and haul productivity, fragmentation size distribution affects energy consumption and throughput in crushing and milling. According to Napier-Munn (2015), most of the energy consumer in the base and precious metal mines is attributed to size reduction, and it is used inefficiently. Blasting is cheaper and more energy efficient as compared to milling. Efficient blasting can save up on energy and increase plant throughput.

2.1. Review on fragment size distribution

Fragmentation size distribution can be computed in two ways; using Rosin Rammler equation (Vesilind, 1980) and cumulative size distribution curve which is plotted with size (X) on x-axis and percentage (P or R_x) in y-axis. The distribution R_x represents the weight of material that is smaller than the given particular size. R_x varies between 0 to 100% or 0 to 1 as shown in **Error! Reference source not found.**. Two important parameters that define the characteristics of the distribution are mean particle size, X_{50} and uniformity index, n. From Rosin Rammler equation they are represented as follows:

$$R_x = 1 - \exp\left[-0.693\left(\frac{X}{X_{50}}\right)^n\right] \tag{1}$$

Where R_x is mass fraction passing on the screen of size X, X_{50} is mean particle size, and n is uniformity index usually between 0.5 and 2.

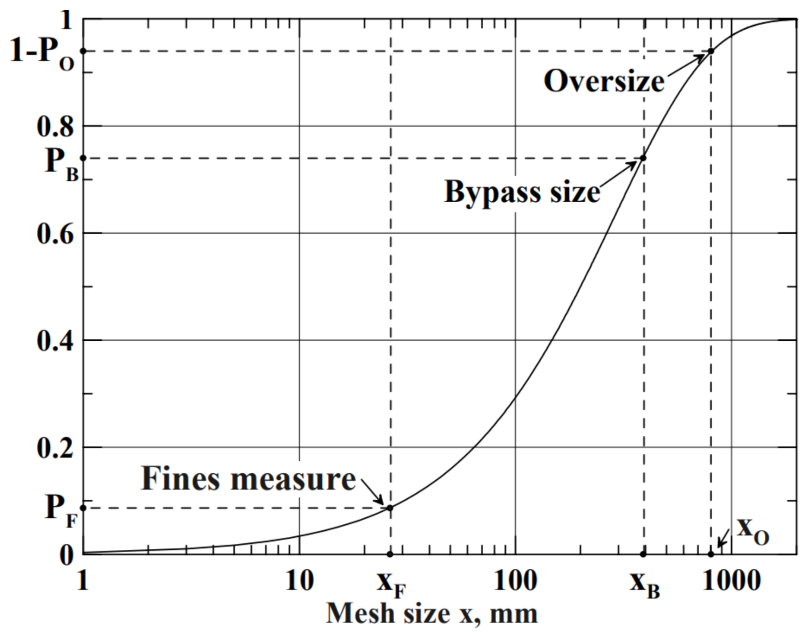

Fig. 1: Fragment size distribution (Ouchterlony, 2003)

Description of quantities on distribution curves can be made referring measure of average fragmentation X_{50}, percentage of fragments larger than a certain size P_o, percentage of fragments smaller than a certain size P_F or any other percentage, P_y.

Shovel productivity is influenced by uniformity index and fragmentation size (Brunton, Thornton, Hodson, & Sprott, 2003; Cottee, 2001). Uniformity index has a great influence in fill factor; a decrease from 1.5 to 0.5 uniformity index, increases fill factor by 15% (Cottee, 2001). The slope of cumulative distribution relates to uniformity index; as the curve gets steeper, uniformity index increases and shovel productivity decreases due to low fill factor as described in **Error! Reference source not found.**. The bottom row in **Error! Reference source not found.** (left) has low uniformity index, where, due to the presence of different sizes, the particles fit together better and improves bucket fill factor.

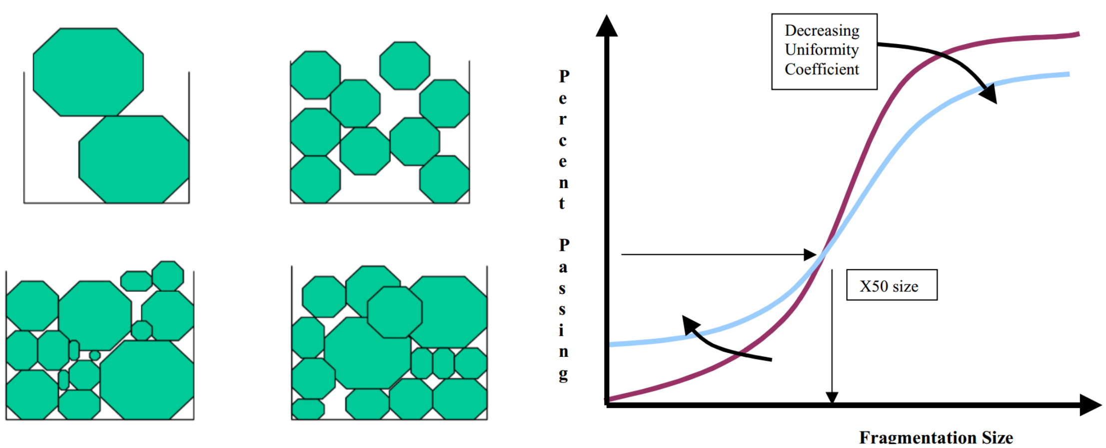

Fig. 2: Diagram and graph showing effect of n in fill factor (Cottee, 2001).

Productivity of shovel truck system is efficient on size range1/6 to 1/8 of shovel bucket capacity (Jimeno, Jimeno, & Carcedo, 1995). In mining, oversize materials are termed depending on loading equipment or crusher capacity. Jimeno, et al. (1995) determined that oversize material are the ones larger than 0.7 times the smallest dimension of loading bucket. According to Kanchibotla, Valery, and Morrell (1999) loading and hauling operations are affected by fragmentation bigger than 250mm.

Factors affecting fragmentation distribution and properties of blasted muck pile are categorized in two groups; the first group is controllable parameters; such as blasting design parameters and explosive related parameters and second group are uncontrollable parameters, containing physical and geomechanical properties of intact rock and rock mass (Kulatilake, Qiong, Hudaverdi, & Kuzu, 2010). There are several models which have been established to predict blasting fragment size distribution. The most popular model is Kuz-Ram developed by C. V. B. Cunningham (1987).

$$X_n = AK^{-0.8}Q^{\frac{1}{6}} \times \left(\frac{115}{RWS}\right)^{\frac{19}{20}} \tag{2}$$

Where X_n is the mean particle size (cm), A is rock factor (varying from 0.8 to 22 depending on hardness and structure), K is powder factor (kg/m^3), Q is mass of explosive per hole (kg) and RWS is the weight strength relative to ANFO; 115 is RWS of TNT.

Two common methods are used to assess fragmentation size distribution in mining; sieving and photographic techniques. The challenge has been obtaining a representative sample for the whole blasted muck pile. Sieving is more accurate but it is costly and impractical for routine implementation in surface mines due to high volumes involved (Beyglou, 2016). Split desktop image processing is one commonly used programs in computing fragmentation distribution. The downside of image analysis systems is, they cannot resolve particles smaller than the size determined by pixel resolution and obtaining a representative sample. (Brunton, et al., 2003)

2.2. Characteristics of rock fragments at different size distributions

Shovel digability depends on fragmentation size and muck pile swell and looseness. Presence of boulders in muck pile necessitates more time to negotiate the boulders and hence increase loading time. Fill factor and payloads are affected by fragmentation size, distribution of size ranges and material angle of repose.

Void ratio is defined as the ratio of the void volume to the total volume of bulk material including the voids. Void ratio is directly related to the fragmentation level, and it is an indication of how the available room in a bucket have been used (Doktan, 2001). Void ratio determines bulk density; increase in fines lowers void ratio, increases bulk density and therefore improve bucket load and payload.

The angle of repose is the angle at which blasted rock fragments can remain stable. The angle of repose increases with the increase in mean particle size of a muck pile. Looseness and angle of repose affects the bucket fill factor and digging cycle time of the loader and therefore the productivity (Singh, 2006).

Fines result from over crushing of the rock during blasting. Fine materials act as a lubricant between coarser materials in a muck pile, they improve bucket penetration and reduce loading time. From this discussion, a reasonable percentage of fines reduces void ratio, increase fill factor and eventually payload. On the other hand, a higher percentage of fines lowers the angle of repose and cause the material to flow out of the bucket without heaping. Poor fragmentation results into production of boulders that can be too large to be handled by truck and shovel or affects loading operations by reducing productivity and increase the overall operations costs.

2.3. Impacts of fragmentation size distribution on productivity

The most common relationship used to calculate shovel productivity relates production rate to bucket capacity, material characteristics and operations efficiency.

$$P_R = \frac{B_c \times O_e \times B_f \times S_f}{C_t} \tag{3}$$

Where P_R is shovel productivity, B_c is bucket capacity, B_f is bucket fill factor, S_f is material swell factor O_e is the percentage of time that a machine actually operates and C_t is the cycle time. Fragmentation size affects the fill factor and cycle time, but it is not the only factor. From this expression, the effect of fragmentation size distribution on shovel productivity is not studied.

Beyglou et al. (2017) conducted a study to determine fragmentation for efficient loading and crushing. They came out with three observations; first, ore type does not have an impact on loading productivity. Second, fill factor is affected by the percentage of fines in the distribution; very fine fragmentation has lower fill factor compared to medium fine fragmentation and third, fill factor decreases with the increase in fragmentation size. These relationships were presented, but they did not establish any expression which relates them to shovel productivity.

Cottee (2001) conducted a study to determine the impact of fragmentation on truck and loader productivity. He determined that blast design like holes spacing and burden and explosive properties such as explosive strength and detonator timing affect fragmentation and muck pile shape. Fragmentation size affects loader digability and fill factor. Trucks productivity is affected by fragmentation through fill factor, payload and cycle time resulting from loading time and waiting time at the loader. He did not establish expression for truck-shovel productivity in his work.

Sanchidrián and Ouchterlony (2017) established a formula to predict productivity of excavators from rock mined by drilling and blasting in iron and copper open pit mines. Data from 20 blasts with rock ranging from medium to very high strength were used with three blasting agents; ANFO, water-gel and emulsion blends. Powder factor used ranged from 0.88 to 1.45kg/m^3. The formula developed was;

$$Q = Q_0 e^{-k \times \frac{f_s}{B_p}} \left[\frac{\sigma^2}{\left(E - E^0\right)^2 + \sigma^2} \right] \tag{4}$$

Where; Q_0 is the maximum excavator productivity, $e^{-k \times \frac{f_s}{B_p}}$ accounts for the effect of rock characteristics and dipper capacity where, k is a coefficient, B_p is bucket nominal payload, and f_s is rock strength factor. $\left[\sigma^2 / \left(\left(E - E^0\right)^2 + \sigma^2 \right) \right]$ is blast factor including the influence of blast design such as rock properties, fragmentation and resultant heave. E_0 is energy powder factor at which excavator efficiency is maximum (E_0 depends on rock properties and loader type), E is the energy powder factor used, and σ is a scale factor.

They concluded that the productivity of shovel is an indicator of blast performance. As energy powder factor increases also productivity increases until it reaches critical factor E_0 where increase provides no further improvements. The shortcoming in this model is that the detonation delay between rows which influences muck pile property was not considered in the model.

Osanloo and Hekmat (2005) conducted a study at Gol-e-Gohar mine to predict shovel productivity. Fragmentation in Gol-e-Gohar mine is mainly affected by water table, many discontinuities and improper use of explosives. They established that the main factor affecting shovel productivity is bucket fill factor which is influenced operator skills and fragmentation size; other factors are swing period and angle, cycle time and job efficiency. Fragmentation composition has an effect on bucket fill factor, swell factor, job efficiency and rock density. They developed a model for shovel productivity (SP) as:

$$SP = 1769 - 9.63d_{50} + 444.45n - 3.37nd_{80} \quad (5)$$

Where, d_{50} is the average particle size, n is the uniformity coefficient, and d_{80} represent 80% weight of material less than a certain size. They concluded that the larger the particles, the lower is shovel productivity. From this relationship, they established d_{80} that ensure higher shovel productivity is between 20 and 40 cm.

Although several factors are indicated to affect shovel productivity such as operator's efficiency, blasting effectiveness, swing angles and others, they are not included in the model. The model assesses the effects of fragmentation after blasting; it does not consider the effects of blast design and explosive properties on resulting fragmentation.

Brunton et al. (2003) conducted a study to determine the effect of fragmentation on hydraulic excavator dig time. They studied the effect of several fragmentation parameters on dig time such as P_{20}, P_{50}, and P_{80}, uniformity index, top size and percentage of material passing 250 mm. They determined that dig time responds more to P_{80}; as fragmentation becomes coarser, dig time increases. Fragmentation size and number of passes affect loading time. Lowering P_{80} from 600mm to 200mm resulted into 26% improvement on dig time and therefore increased productivity.

Limitations of this study is, it did not include the effects of other muck pile parameters such as muck pile looseness and material ability to flow, fill factor and operators digging strategy. The study is a post-blasting assessment.

Doktan (2001) studied the impact of fragmentation size on truck shovel fleet performance. He determined that, fragmentation impacts load and haul on digability (dig time) and bucket payload (void ratio and fill factor). He established the relationship of dig times with Rosin-Rammler parameters X_{50} and uniformity index as;

$$Dig\ time = a - b \times X_{50} \times n \quad (6)$$

Where, a and b are constant equal to 8.9942 and $-6.8706e^{-2}$ respectively, X_{50} is mean fragmentation and n is uniformity index. Better fragmentation resulted into reduced dig times, improved shovel productivity and increase truck payload.

Similar to previous models, Doktan did not include the effects of other muck pile properties and operators digging strategies in estimating digging time. The model deals with post-blast assessment; it does not consider the effects of blasting to resulting fragmentation.

3. Discussion

Shovel productivity is influenced by number of bucket loads, fill factor and cycle time. From reviews, it is clear that these are affected by fragmentation distribution. Productivity declines with an increase in particle size at which average dig times increase and fill factor decreases. Similarly, dig times and fill factor are affected by material looseness, operator's skills, loading strategies as well as bucket capacity although in the discussed models they were not included. Since shovel productivity is affected by many other factors than fragmentation distribution, it requires more involving models to establish.

Although it is clear that fragmentation affects productivity, it is not clear how and to what extent and therefore difficult to determine the target for drill and blast operations (Beyglou, 2016). So far trial and error and empirical experimentation are used to describe the influence of fragmentation in shovel productivity similar to the ones discussed. Further studies on the effects of fragmentation on productivity is required to develop a predicting model that can be modified depending on site specifics.

In estimating payload, the interaction between different fragmentation sizes and its effect on void ratio are not discussed. There are models developed to predict void ratio and payloads from mixed fragmentation sizes as the one discussed by (Doktan, 2001) considering relative quantities of fragmentation size, effective size and specific packing density of each fragment. If they are applied, they will offer a better prediction of payloads.

The developed models are focused on post-blasting assessment, (Brunton, et al., 2003; Osanloo & Hekmat, 2005). The collective effort towards improving shovel productivity and other downstream operations should focus on improving blasting effectiveness. Studies conducted by (Cunningham, 2005; Singh, et al., 2016; Singh and Narendrula, 2010) which describe relationships of blasting parameters with uniformity index and fragmentation size distribution and can be used to design blast for targeted results.

4. Conclusion

Fragmentation size distribution affects shovel production on digability and fill factor. Digability impacts loading time and energy used in loading. Truck productivity is also affected on payload, loading time and waiting time at the loader.

There are several models which have been developed to define the relationship between fragmentation sizes and shovel productivity; most of them are developed from post blasting assessment and exclude significant factors affecting productivity. Establishment of more inclusive models requires a further study into the factors affecting productivity and how they influence each other.

A more collective study should include blast effectiveness because fragmentation distribution is the product of blasting. Blasting should be able to provide fragmentation size distribution which ensures efficiency of downstream processes. This can be done by manipulating blasting set up if the target fragmentation distribution is known.

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