MODELLING FINES IN BLAST FRAGMENTATION AND ITS IMPACT ON CRUSHING AND GRINDING

Sarma S Kanchibotla, Walter Valery and Steve Morrell

Julius Kruttschnitt Mineral Research Centre
The University of Queensland

INTRODUCTION

In the mining industry blasts are usually designed to fracture the in-situ rock mass and prepare it for excavation and subsequent transport. The run of mine (ROM) fragmentation is considered good when it is fine enough and loose enough to ensure efficient digging and loading operations. Mining optimisation strategy is hence usually focussed on minimising total mining costs and maintaining these ROM fragmentation characteristics. Although this approach ensures an efficient mining operation it ignores the potential impact on crushing and grinding. Investigations by several researchers have shown that designing blasts to produce ROM fragmentation to optimise crushing and grinding performance, enhances the overall efficiency and profitability (Eloranta 1995, Kojovic et al., 1995, Bulow et al, 1998, Kanchibotla et al 1998, Scott et al 1998, Simkus and Dance, 1998).

Field experimentation in this area is often found to be difficult because of high implementation costs and insufficient understanding about the effect of fragmentation at different stages in a comminution circuit. Modelling and simulation of blasting and comminution processes provide a more economic alternative to explore the impact of blast design changes on the down stream operations (Kanchibotla et al, 1998, Kojovic et al, 1998, Adam and Siddall 1998, Bulow et al, 1998). However, the reliability of such simulations depends on:

- The ability of the models to reproduce the physical processes that take place

- Characterisation of rock mass in terms of its blastability and comminution characteristics.

- In the case of blast modelling the ability to predict fines (-10mm) has been found to be particularly important as this fraction has a significant effect on mill throughput.

ROCK / ORE CHARACTERISATION

The characterisation of rock /ore is of fundamental importance for the design and optimisation of any mine to mill process. Characterisation of ore for blasting will be different from that for crushing and grinding operations. For example, the rock mass structure in addition to its strength is very important for blasting, whereas the micro fracture network, grain size and grain characteristics may be important in comminution processes such as crushing and grinding. Therefore it is essential to understand these differences and characterise the rock mass in terms of its blastability and comminution properties.

Blastability

Blasting will loosen the existing rock mass structure to liberate rock blocks as well as creating new fractures within the intact material. Therefore any meaningful description of rock mass blastability should be a function of mechanical properties of intact rock (such as stiffness and strength) and the rock mass structure (size of 'insitu blocks'). Zones within a mine that are of similar strength and structure should blast in a similar way and hence form a blasting domain.

Structural properties

Structural parameters can be determined through scan-line mapping of the exposed bench face or estimated from visual inspection. The volumetric joint count (Jv) is a simple measure of the degree of jointing or the *in situ* block size of a rock mass. The number of joints intersecting one unit of rock mass is defined as the volumetric count and can be estimated from a joint count made within a window defined on the face. In the case of a new deposit, structural parameters can be estimated using rock quality designation obtained from exploratory diamond drilling.

Mechanical properties of rock

The mechanical properties of rock such as density, Young's modulus and uniaxial compressive strength (UCS) influence the rock mass blastability and can be determined from laboratory tests. The samples for conducting these tests are usually obtained from the blast muckpiles. In order to properly characterise the rock strength it may be necessary to conduct tests on a large number of samples, which may be expensive. In such cases the UCS can be

obtained indirectly from point load tests performed on irregular samples. Point load testing (Broch and Franklin 1972) is inexpensive and therefore can be performed cheaply on a number of rock samples.

Comminution characteristics

Comminution is the reduction of size of a particle through the application of mechanical energy and is usually applied to the crushing and grinding processes. It is necessary to understand the comminution properties of different ore types to optimise the integrated mine-mill operation.

The JKMRC has developed a 'drop weight test' to determine the breakage characteristics of rocks. This test is used to break rocks in a range of sizes under a range of energies. The results are condensed in a relationship between the T10 and the specific breakage energy as follows:

$$T10 \quad = \quad A (1- e^{-bEcs}) \tag{1}$$

where A, b $\quad = \quad$ ore specific parameters

Ecs $\quad = \quad$ specific breakage energy (kWh/t)

T10 $\quad = \quad$ % of ore passing $1/10^{th}$ original particle size.

The T10 relationship with respect to the rest of the product size curve is expressed as a matrix of Tn values where n = 2,4,25,50,75. By convention the T10 is the % passing $1/10^{th}$ of the original particle size, whilst the T50 is the % passing $1/50^{th}$ etc. The ore specific parameters (A and b) and the breakage matrix define the breakage characteristics of a rock at different energy levels. A detailed description of the tests for determining the comminution properties is given by Napier-Munn et al (1996).

Kojovic and Wedmair (1995) found that the breakage strength of the post blast fragments is less than the strength of fragments not subjected to blast loading. Investigations by Nielsen and Kristiansen (1995) and Kojovic et al (1995) found that the amount of applied blasting energy and the rate of application will influence the comminution properties of ore.

Measurement while drilling (MWD)

Laboratory methods used to determine the mechanical properties and comminution properties of rock have two main disadvantages. Firstly, they are biased towards stronger rock elements because they survive better in the sample preparation procedures. Secondly, the time required to obtain the data may be too long to implement any design changes if there is change in the rock properties. An alternative is to use the data provided by the drill monitors. Some of these monitors measure a range of drilling parameters which can be related to the mechanical properties of the rock mass (Hendricks and Peck 1995). Figure 1 shows the rock strength reported by the Aquila drill monitor for each hole in a blast pattern. Such information can be used to study the variation in the geology in a pattern and for explosive loading.
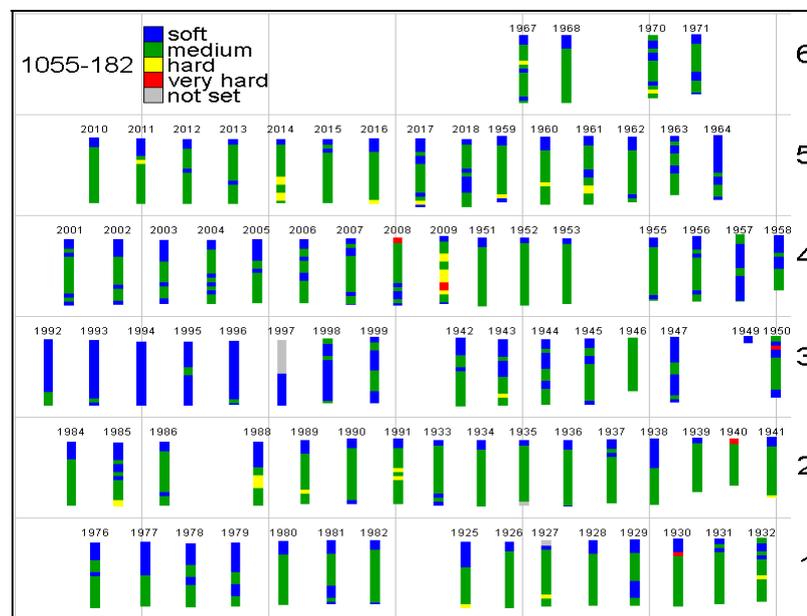

Figure 1. Blasthole geology reported by the drill monitors

Even though enough correlation is established between the MWD parameters and rock strength, further research needs to be carried out to establish appropriate correlations between the structural properties and comminution properties of a rock mass with its MWD parameters. Once these relationships are established, the MWD parameters can then be used to design and control the blasting and comminution processes in real time.

MONITORING KEY PARAMETERS

Monitoring the key inputs and the resulting outputs at every process is very important in understanding and modelling that process. In recent years, significant advances have taken

place in monitoring the equipment used in mining and mineral processing operations. It is now possible to monitor the performance of equipment such as shovels, crushers and mills in real time. However there are very few techniques to measure the size distribution of rocks.

Fragmentation assessment

The size distribution of rocks influences the process efficiency at different stages of mining and milling operations. Therefore it is necessary to measure the size distribution of rocks at different stages of a mine-mill process such as:

- ROM fragmentation (after blasting)
- after primary crushing
- after stockpile as mill feed.

The traditional method of assessing the size distribution of rocks is to sieve a representative sample. This technique is feasible for measuring the crusher product and mill feed but is very expensive and time consuming for measuring ROM. The second method is to assess the size distribution indirectly based on production statistics (eg. extent of secondary breakage, digging efficiency, crusher throughput) that depend on fragmentation. The third method is to use image analysis techniques. In this method, images of the rocks are captured by a camera and analysed to assess fragmentation.

The JKMRC in collaboration with the University of Arizona has developed an image analysis system called Split to assess size distribution of rocks on muckpiles, on discharging dump trucks and on conveyor belts. In the past two years this system has been installed at several mine sites. However the experience of the JKMRC and several other researchers show that the accuracy and reliability of image based fragmentation assessment system depends on the following issues.

- Sampling errors
- Quality of images
- Fines correction

All the above issues are site specific and hence need site calibration.

Sampling errors

Systematic bias in the process of taking an image can introduce serious errors. Generally the size distribution of ROM fragmentation is obtained from the images of blasted muckpiles. In hard and massive rock blasting the surface of the muckpile is usually coarser because the rocks in this zone are usually generated from the stemming region and from the front row containing back break (Figure 2).
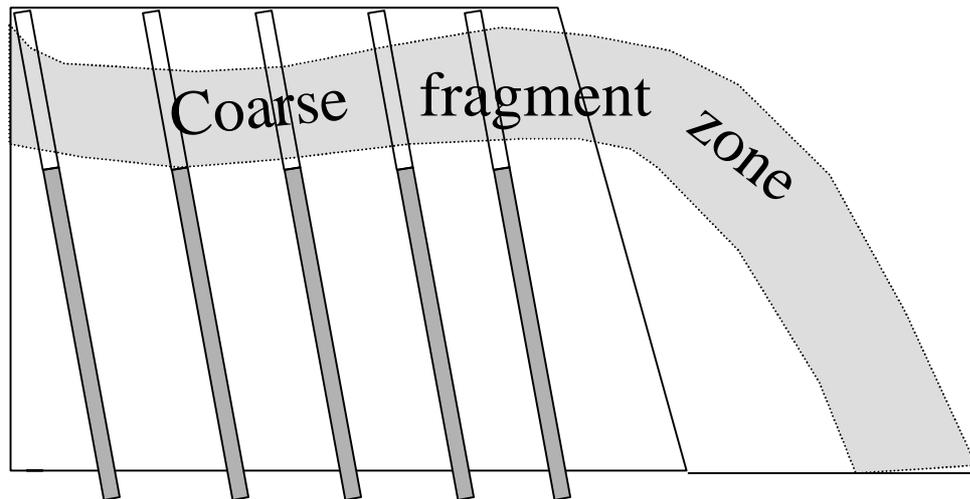

Figure 2. Sampling bias from muckpile images

In order to avoid this sampling bias, images should be obtained at regular intervals while digging the muckpile or during the material handling process, such as from the backs of haulage trucks or in the buckets of the loader. However, acquiring quality images of a loader bucket is difficult and hence, the JKMRC has developed a system to grab the images from the back of trucks while unloading into the crusher (Atasoy et al 1998). The size distribution of crusher product and mill feed can be obtained from the images taken from the conveyor belts.

Quality of images

It is widely acknowledged that any imaged-based system must have the ability to identify particle-boundary pixels in the image and subsequently group these pixels in data entities that represent the different fragments in the image. Particle-boundary pixels are determined by identifying the high grey level gradients among neighbouring pixels in the given image. However, this assumption is only partly true, because the surface texture and shadows can also create high grey level gradients. High grey level gradients due to surface texture can not be eliminated because they are part of the image but their influence can be mitigated by using

certain image processing alogorthims. On the other hand, shadows projected by external elements or other particles, are more detrimental to the image segmentation stage than surface-texture shadows, because they are not part of the image and should be eliminated during image acquisition. Shadows can be eliminated by using intense and even lighting on the active image area. Providing uniform lighting conditions is very critical for getting reliable results from any image analysis system. This was found to be a challenging task especially for truck based systems.

Fines correction

Fines are not properly taken into account in images of rock fragments because of two reasons. Firstly, they are not always present on the surface because of segregation due to vibration, settling, wind and rain. Secondly, even if they are visible on the surface, the individual fragments are too small to be delineated properly because of resolution limitations in the digital image.

The Split system accounts for fines in two ways (Kemeny, 1994). Firstly it determines the minimum size of fragments (referred to as the *fine-size*) that can be delineated depending on resolution and scale of the image. Secondly it assumes that a percentage of the non-delineated area contains fines. Figure 3 shows the comparison of size distributions using Split with different fines correction and sieving results.
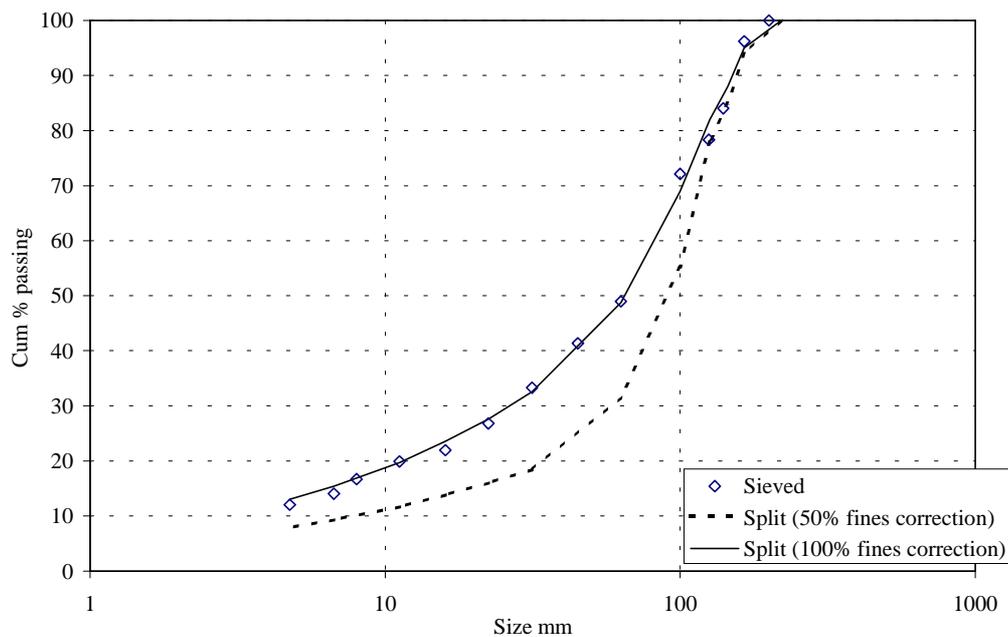

Figure 3. Comparison of Split estimates with and without fines correction

The results from the Figure 3 shows that there is good correspondence between the Split results and sieved results for +100mm rocks whereas for –100mm rocks, the 100% fines correction gave better correspondence than with 50% fines correction. This correction factor depends on the resolution of the image, lighting factors and the way the rock is distributed in the image. That is why it is advisable that the fines correction should be determined on site by calibrating with a measured sizing.

Calibration of the Split system for ROM images is more difficult as sieving is much more expensive. It is generally accepted that in hard ores most of the fines (-10mm) present in the mill feed are produced by blasting. Therefore the fines end for ROM can be estimated from the images taken from the crusher product conveyor or Sag feed conveyor. The entire ROM size distribution can be constructed by merging the coarse end of the distribution (estimated from muckpile and truck images) with the fines end (estimated from the crusher product conveyor or sag feed conveyor images).

MODELLING

Understanding the mechanisms and interaction between different processes in the mine-mill chain, modelling the key processes and integrating them is of vital importance to the integrated mine to mill model. The key processes identified for modelling are:

- Blast fragmentation

- Primary crushing

- SAG milling

- Ball milling

Blast fragmentation modelling

A variety of modelling approaches ranging from purely empirical to rigorous numerical models have been used to predict fragmentation from blasting. Amongst them the Kuz-Ram model developed by Cunningham (1983) is probably the most popular. Cunningham (1983) modified the Kuznetsov's (1973) empirical equation to estimate the mean fragment size($\bar{x}$) and used the Rossin-Rammler distribution to describe the entire size distribution. The uniformity exponent of the Rossin-Rammler distribution is estimated as a function of blast design parameters (Cunningham 1987).

Research at the JKMRC and elsewhere has demonstrated that the Kuz-Ram model under estimates the contribution of fines in the ROM size distribution (Kojovic et al.1995, Comeau 1996). Traditionally blasting engineers are interested in the +250mm size because it affected the loading and hauling operations which are part of the mining function. However, in operations where the price is dependant on the percentage of fines in the final product (eg. iron ore operations and coal) and where the throughput is affected by the fines (-25mm), it is important to estimate the fines with reasonable accuracy.

One of the reasons for under estimation of fines in the Kuz-Ram model may be that the fines in a blast are generated by a different breakage mechanism compared to coarse fragments.

JKMRC Fragmentation Modelling Approaches

Fragmentation due to blasting is produced by two mechanisms. One is related to the compressive-shear failure of the rock (mainly of the rock matrix) close to the blastholes, while the second mechanism is the tensile failure of the rock mass. Fines in a blast are generated predominantly by the crushing of rock around the blast hole due to compressive-shear failure. The coarse fragments are generated predominantly by tensile failure beyond the crushing zone (Figure 4). The JKMRC has therefore developed two techniques for modelling the fine end of the distribution.
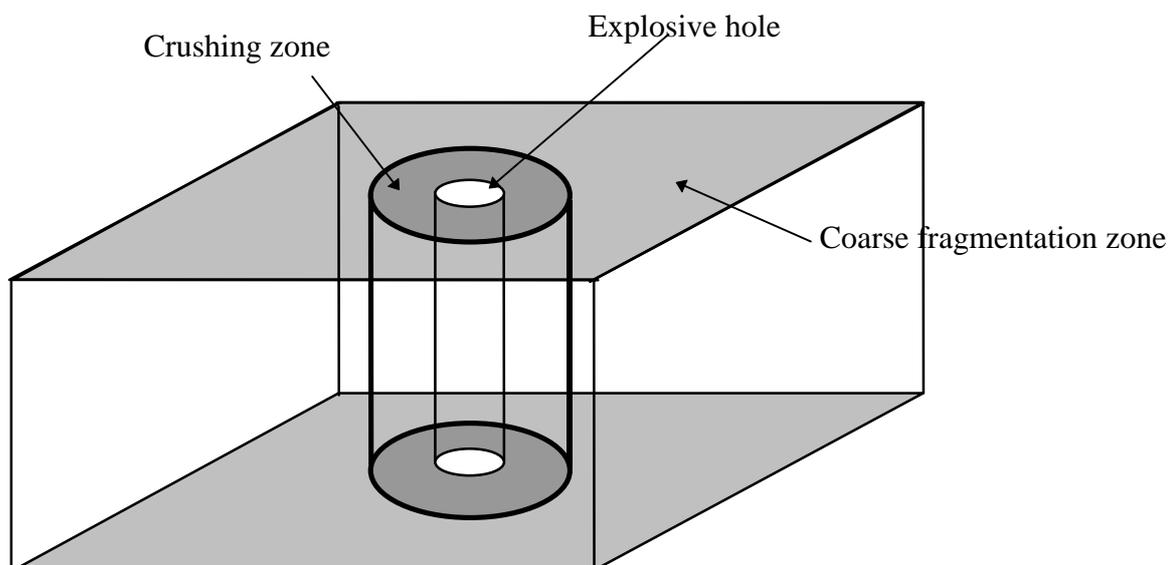

Figure 4. Schematic of the Crushed Zone Approach

Small scale blasting

The first of these is based on the controlled blasting of 200 mm diameter drill cores or 300 – 400mm size blocks in the JKMRC's blasting chamber. This approach is a development of work undertaken by Stagg et al (1992) at the USBM to study the generation of fines in blasting. Using the blast chamber the fines distribution was determined and combined using cubic splines with the coarse part of a second distribution which was generated using a conventional Kuz-Ram approach (Djordjevic 1999).

Crushed zone approach

In the second, an approach similar to that used in the Kuz-Ram model has been adopted but with some modifications in rock factor and energy factor. The rock factor used in this model is based on rock mass structure and rock matrix properties similar to that proposed by Lilly (1986) and Grouhel (1992). The energy factor is based on the effective energy, which is a function of explosive properties, rock properties and the confinement provided in the blast (Sarma 1996).

However the major difference between this approach and conventional Kuz-Ram is that in this method it is hypothesized that the fines are produced by the crushing action of the explosive adjacent to the blast holes. A cylinder of rock around each hole is therefore defined within which crushing takes place (Figure 4). The radius of the cylinder, and hence its volume, is determined by calculating the point at which the radial stress around the blast hole exceeds the dynamic compressive strength of the rock.

Currently a working size of 1mm is used to define the coarsest particle that results from crushing. This has been chosen on the basis of results from a number of mines where ROM sizings were available. It is expected, however, that this size is dependant on grain size of the rock and may be determinable from small scale blast results.

Having determined the crushing zone radius around each blast hole, and hence its volume, and knowing the number of blast holes the volume of crushed material (-1mm) can be calculated (V_{crush}). As the volume of rock blasted (V_{br}) is also known the % of blasted rock smaller than 1mm can be estimated from:

$$\% \text{ -1mm} \quad = \quad 100 \times V_{crush}/V_{br} \tag{2}$$

The uniformity index for the fine end of the distribution is then calculated by substituting the %-1mm value, 1mm and a characteristic size in the Rosin-Rammler equation. The uniformity index for the coarse end is estimated using the equation as proposed by Cunningham (1987). The two distributions join at a characteristic size which is dependent on rock mass properties (Figure 5). The experience so far suggests that X_{50} as the characteristic size gives good results for stronger rocks (UCS > 50 Mpa) and X_{90} as the characteristic size gives better results for very soft rocks (UCS < 10 Mpa). It is likely that for intermediate strength rocks the point where the two distributions are joined will vary between the X_{50} and X_{90} values.
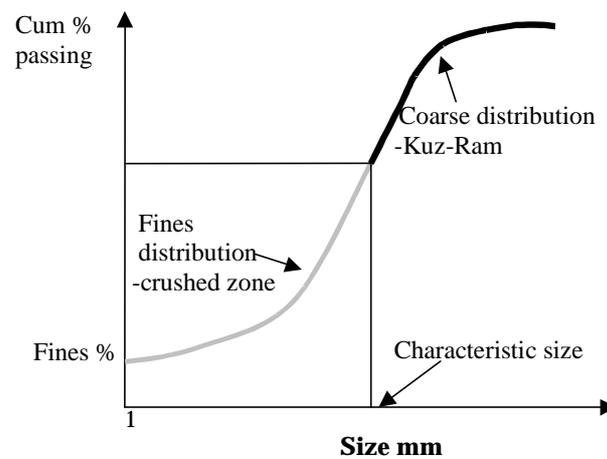

Figure 5. Fines and coarse size distribution in ROM

Model validation

The above model has been used to predict the ROM fragmentation from several mine sites and the results so far suggest that the size distributions predicted by the crushed zone approach are far superior to those from the conventional Kuz-Ram model, especially at the fines end of the distribution (JKMRC 1998). To provide data to validate the crushed zone approach the JKMRC team monitored a blast (blast #760043) at Cadia Hill and applied the crushed zone approach to predict the ROM fragmentation.

Cadia Hill is Newcrest Mining's newest mine which began full operation in June 1998. The company has its own mining fleet consisting of two H655 Demag hydraulic shovels and ten CAT 793C haul trucks of 235 t capacity. The plant includes the world's largest (40ft or 12.2 m diameter) SAG mill and ball mills.

The rock mass properties, explosive properties and blast design parameters used in this study are given in Table 1 and structural properties are derived from the RQD data shown in Figure 6. Since the rock is hard and fissured the rock factor for the Kuz-Ram model was assumed as

10. However, for the JKMRC model the rock factor is derived as a function of structural and mechanical properties of the rock mass and the blast geometry (JKMRC 1998).

Table 1. Rock properties, explosive properties and design parameters for blast #760043

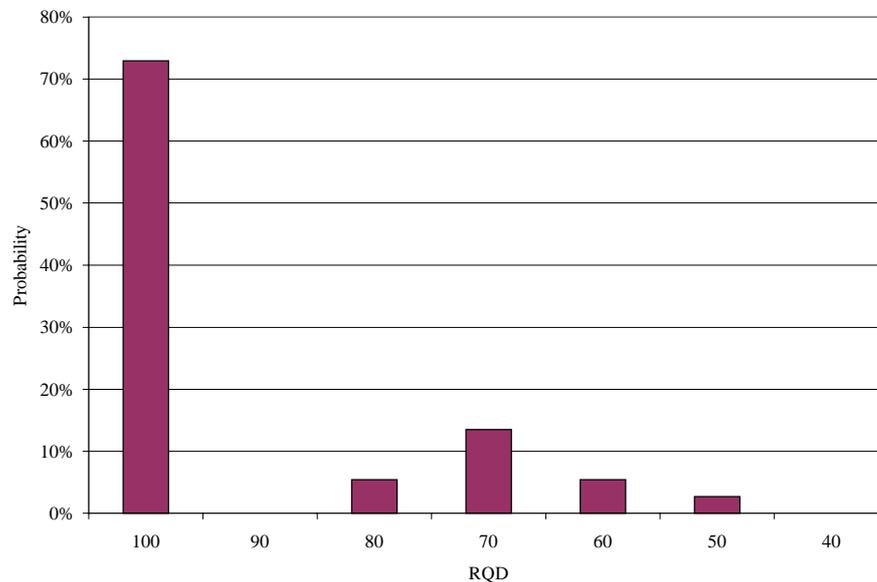| Rock mass properties	Blast #760043
Rock type	Monzonite
Density t/m3	2.60
Young's modulus GPa	62.00
Uniaxial compressive strength MPa	127.00
RQD (Mode value)	100
Blast design parameters	
Burden m	6
Spacing m	7
Hole depth m	16.5
Hole diameter mm	229
Explosive wt kg	593
Bench height m	15
Stemming length m	4.50
Subdrill m	1.50
Explosive properties	
Explosive	Titan 2070g
Density g/cc	1.2
VOD m/s	4950
RWS (ANFO = 100)	80

Figure 6. RQD of monzonite in blast #760043

Fragmentation photographs were taken at the post blast muckpiles, at the back of trucks, at the crusher product conveyor and at the sag mill feed conveyor. The images were processed using the Split system to obtain the size distributions of ROM, crusher product and Sag mill feed. A

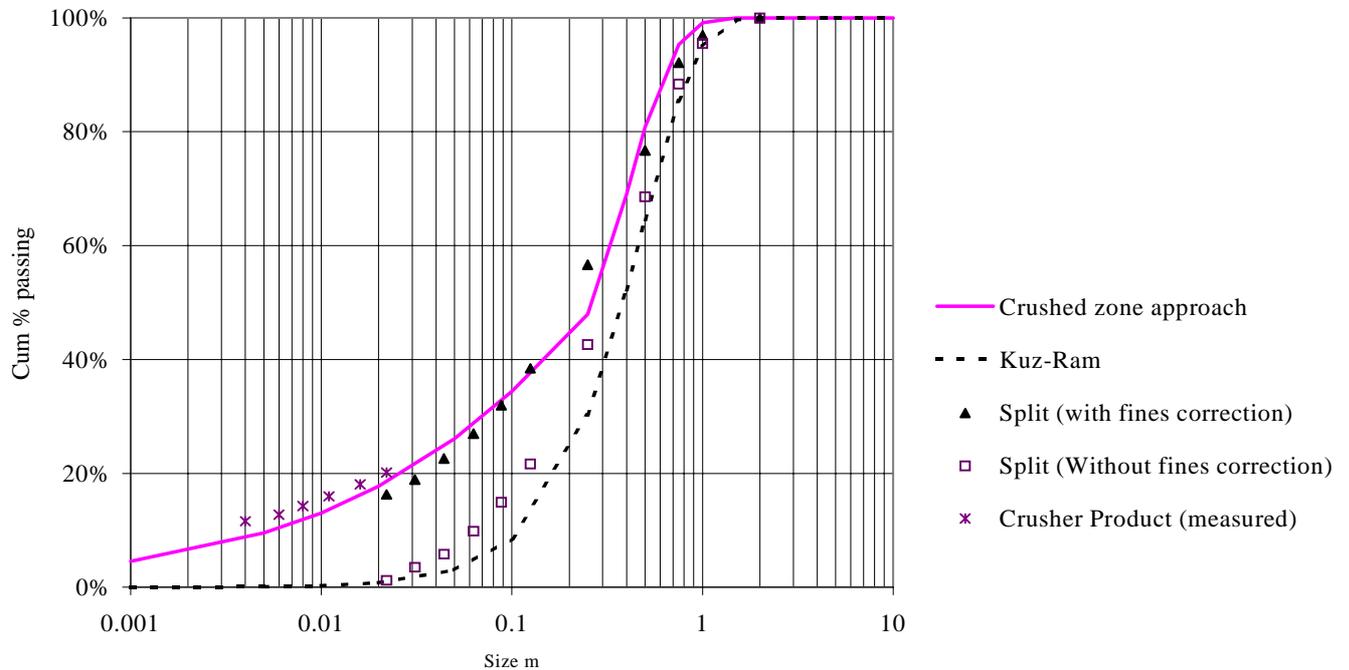comparison of ROM size distribution predicted by the models and by the Split system is shown in Figure 7.

Figure 7. Comparison ROM estimated by the models and Split

The coarse end of ROM size distribution from Split was obtained from 10 muckpile images and 18 images taken from the back of trucks. The results from Figure 7 show that the ROM predictions from crushed zone approach matches with the fines corrected split estimates where as Kuz-Ram predictions matches with the uncorrected split estimates.

Comparison of measured crusher product with the uncorrected Split estimate suggest that most of the –10mm in the crusher product are generated by the primary crusher. However, measurements from sieved ROM and crusher product show that most of the –10mm in the crusher product is derived from the ROM and is generated by blasting. Hence the true ROM distribution should approach the primary crusher product distribution in the –10mm range. These results suggest that the Split system with fines correction provides a good match to the true ROM as does the predictions from crushed zone approach. However without fines correction, image analysis will significantly underestimate the fines as does the conventional Kuz-Ram model.

Comminution modelling

The popularity of autogenous and semi-autogenous mills has had a considerable effect on the economics of the comminution stage. However their dependence on the ore feed for grinding media has made them particularly sensitive to ROM size distribution. The JKMRC has been conducting research in understanding and modelling of ag/sag mills for the past three decades and hence are ideally placed to determine the blast fragmentation/milling interactions as well as the effect on further downstream comminution steps. A detailed description of the JKMRC comminution models can be found in Napier-Munn et al (1996).

The crushing and grinding circuits at Cadia were surveyed when the ROM from the test blast was fed to the mill (Valery 1999). The gyratory crusher model was obtained using ROM and crusher product size distributions obtained by the Split system from images of muckpiles, trucks and conveyor belt. SAG mill feed size distribution was obtained by sieving a conveyor belt cut of 10 metres.

The SAG mill and trommel model parameters were determined by numerical non-linear least-squares fitting. The model parameters were adjusted until the model 'best' reproduced the observed product as closely as possible from the corresponding feed to the unit and the operating conditions. This process also provided estimates of data fit accuracy and parameter estimation accuracy. All survey data sets from the SAG mills were fitted and the fit to the data was very good.

SIMULATING THE IMPACT OF BLASTING ON MILLING PERFORMANCE

The blast fragmentation models and the comminution models were then combined together to study the impact of blast design changes on comminution circuit throughput. As a first step ROM predictions for blast #760043 using the JKMRC (crushed zone) and conventional Kuz-Ram models were passed through the primary crusher model (with a gap of 160mm) and the SAG mill model to predict their performance. The resulting crusher product and the SAG mill performance are shown in Figure 8 and Table 2 respectively.
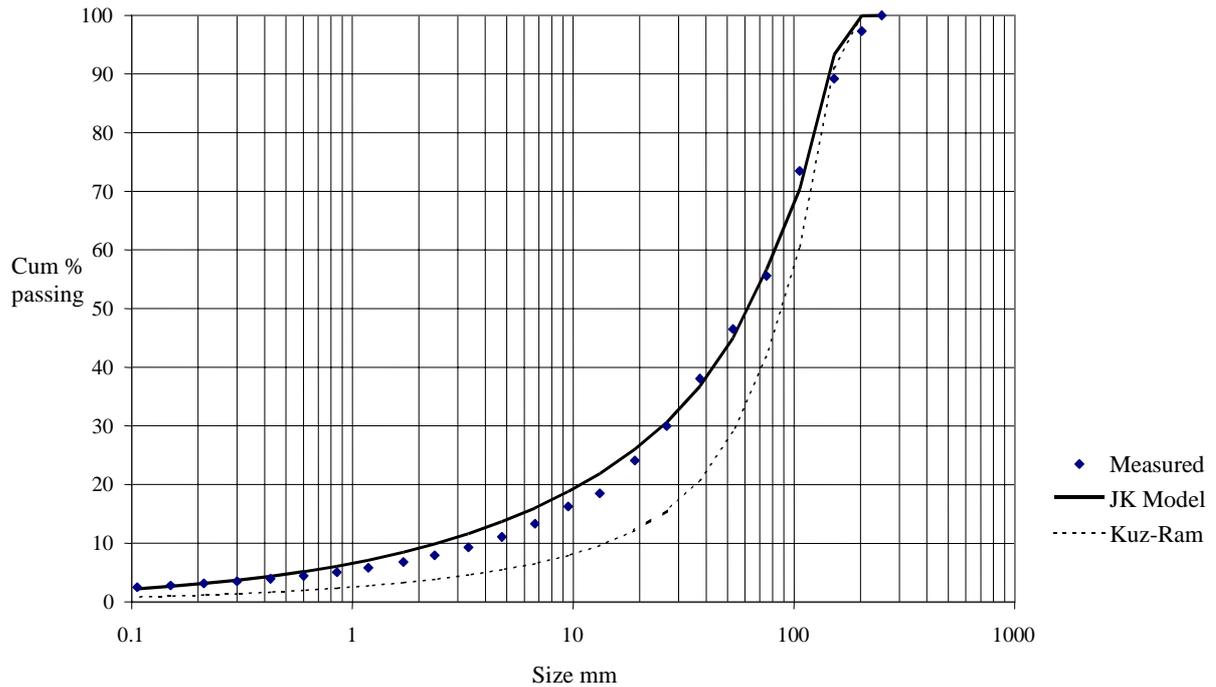
Figure 8. Predicted and measured crusher product (or SAG feed) distribution

Table 2. Comparison of Sag mill performance estimates

	Observed	JK-model	Kuz-Ram
SAG feed rate (t/h)	**2270**	2245	1900
F_{80} (mm)	**121.2**	117.2	130.0
F_{50} (mm)	**60.8**	59.1	86.5
F_{20} (mm)	**14.7**	10.4	32.5
% -50+16mm	**23.7**	20.4	16.6
% -13mm	**18.4**	22.2	10.8

It can be clearly seen from Figure 8 and Table 2 that crusher product and SAG mill predictions using the ROM estimated from the JK model are in much better agreement than with the Kuz-Ram estimated ROM. The mill performance estimated with the Kuz-Ram generated ROM distribution is much lower than the actual. The reason for this is that Kuz-Ram model underestimates fines in ROM as shown in Figure 7.

Impact of blast design changes on SAG mill performance

Once the models were integrated and calibrated the next step was to study the impact of blast design changes on mill performance. The blast # 760043 was chosen as the current bench mark design and two alternate designs were simulated. Once again both the JKMRC and

conventional Kuz-Ram models were used. Design 1 uses a high shock energy explosive (with 5500 m/s VOD) and Design 2 uses a high shock energy explosive coupled with high powder factor. The details of the blast designs are given in Table 3.

Table 3. Blast designs used in the simulation

	Design 1	Design2
Burden m	6	5
Spacing m	7	6
Hole depth m	16.5	16.5
Hole diameter mm	229	229
Explosive wt kg	618	618
Bench height m	15	15
Stemming length m	4.5	4.5
Subdrill m	1.5	1.5
Explosive	Emulsion	Emulsion
Density	1.25	1.25
VOD	5500	5500
RWS	95	95

The ROM estimates from the above designs were fed through crusher and SAG mill models. Comparison between maximum mill throughput and SAG mill feed size observed from blast #760043 and simulated for blast designs 1 and 2 are shown in Table 4.

Table 4. Observed and predicted Sag mill performance for the different ROM estimates

	Blast #760043 Observed	Blast #760043 JKMRC	Blast #760043 Kuz-Ram	Blast Design 1 JKMRC	Blast Design 1 Kuz-Ram	Blast Design 2 JKMRC	Blast Design 2 Kuz-Ram
SAG feed rate (t/h)	**2270**	2245	1900	2310	1890	2505	1858
F_{80} (mm)	**121.2**	117.2	130.0	115.2	130.3	111.3	131.1
F_{50} (mm)	**60.8**	59.1	86.5	55.3	87.3	43.3	89.4
F_{20} (mm)	**14.7**	10.4	32.5	8.4	34.0	4.3	37.6
% -50+16mm	**23.7**	20.4	16.6	20.5	16.6	20.9	16.3
% -13mm	**18.4**	22.2	10.8	24.2	10.2	30.1	8.95

It can be seen from Table 4 that the SAG mill feed predicted using the Kuz-Ram ROM estimates have much less fines (below trommel aperture or 13.0 mm). It is well known that the

grinding rates and consequently throughput are dramatically affected by the amount of fines in the SAG mill feed that is carried through the mill ("free grind" material that passes straight through the grates and trommel).

The JKMRC model simulations showed that blast design 1 should increase mill throughput by 3% and design 2 should increase mill throughput by 12% compared to blast #760043. The JKMRC model simulations were validated at the Highland valley copper mine in Canada where the implementation of blast design changes have resulted in significant increase in mill throughput (Johnston and Simkus 1998).

The observed SAG mill throughput using Kuz-Ram ROM size predictions failed to match the observed throughput and was also found to be insensitive to blast design changes. These results are similar to the findings published by Adam and Siddall (1998) who have also used Kuz-Ram for ROM predictions. The main reason for this insensitivity is that the Kuz-Ram model underestimates the fines in the ROM and hence is unsuitable for mine-to-mill simulations.

CONCLUSIONS

The reliability of any modelling and simulation to explore the impact of blast design changes on the down stream operations depends on the accuracy of rock mass characterisation and the ability to model and measure the amount of fines generated in blasting.

The simulation exercise shown in this paper demonstrates that the conventional Kuz-Ram model underestimates the fines generated in blasting and therefore fails to accurately predict the performance of down stream operations. The study also showed that the image based fragmentation assessment systems underestimate fines unless they have fines correction capability. The JKMRC blast fragmentation model estimates the fines in ROM more reliably and hence its predictions about down stream operations are more reliable.

The simulations with the JK model suggest that the usage of high shock energy explosive with higher powder factor increases the SAG mill throughput significantly. However, in this study the effect of blast design changes on muckpile diggability, back break, ground vibrations and dilution is not estimated. It is essential to take into account these factors while performing any design changes.

ACKNOWLEDGMENTS

REFERENCES

Adam R., and Sidall B. (1998), Blast manipulation or crusher modification ?, Proc. Mine-Mill Conf., Brisbane.

Atasoy, Y., Brunton, I., Tapia-Vergara, F and Kanchibotla, S.S. (1998), Implementation of Split to estimate the size distribution of rocks in mining and milling operations, Proc. Mine-Mill Conf., Brisbane.

Broch, E., and Franklin, J.R., (1972). Point Load Strength Test. International Journal of Rock Mechanics and Mining Sciences, vol. 9, pp.669-697.

Bulow B., Smallbone P., and Walker B., (1998), Blasting for reduced process plant costs at Argyle diamond mine, Proc. Mine to Mill Conf., Brisbane.

Comeau, W., (1996). Explosive energy partitioning and fragment size measurement – Importance of correct evaluation of fines in blasted rock, Proc. of the Fragblast-5 workshop on Measurement of Blast Fragmentation, Montreal 237-240.

Cunningham, C.V.B., (1983). The Kuz-Ram model for prediction of fragmentation from blasting, Proc. 1st Int. Symp. on Rock Fragmentation by Blasting, Lulea, 439-454.

Cunningham, C.V.B., (1987). Fragmentation estimations and the Kuz-Ram model - Four years on, Proc. 2nd Int. Symp. on Rock Fragmentation by Blasting, Colorado, 475-487.

Djordjevic, N., (1998). Two-component Blast Fragmentation Model. JKMRC Internal Report.

Grouhel, P., (1991). An explosive selection technique for optimising blasting at open cut mining operations, M. Sc. Thesis, University of Queensland.

Hendricks, C., and Peck, J., (1995), Applications of GPS and equipment monitoring technology to blasting operations in surface mining, Proc. Sixth High Tech Seminar on State-of-the-Art Blasting Technology Instrumentation and Explosive Applications, Boston.

Eloranta, J. (1995), Selection of powder factor in large diameter blastholes, EXPLO 95 Conference, AusIMM, Brisbane, September, PP 25-28.

JKMRC (1998), Optimisation of fragmentation for downstream processing, AMIRA P483 Final Report.

Johnston D., and Simkus R., (1998), The human side of co-ordinating mine to mill activities at Highland valley copper, Keynote address at the mine to mill 1998 Conference, Brisbane, (Unpublished).

Kemeney J., (1994), A practical technique for determining the size distribution of blasted benches, waste dumps and heap leach sites, Mining Engineering, Vol. 46, No.11, PP 1281 – 1284.

Kanchibotla, S.S., (1994). Models for assessing the blasting performance of explosives, Ph.D Thesis, Univ. of Queensland, Australia.

Kanchibotla S.S., Morrell, S., Valery W., and O'Loughlin P., (1998), Exploring the effect of blast design on sag mill throughput at KCGM, Proc. Mine to Mill Conf., Brisbane.

Kojovic, T. and Wedmair, R. (1995), Prediction of fragmentation and the lump / fines ratio from drill core samples at Yandicoogina, JKMRC Internal report.

Kojovic, T., Michaux, S., and McKenzie, C., (1995), Impact of blast fragmentation on crushing and screening operations in quarrying, EXPLO 95 Conference, AusIMM, Brisbane, September, PP 427-436.

Kojovic T., Kanchibotla S.S., Poetschka N., and Chapman J., (1998). The effect of blast design on the lump-to-fine ratio at Marandoo iron ore operations, Proc. Mine to Mill Conf., Brisbane.

Kuznetsov, V.M., (1973). The mean diameter of fragments formed by blasting rock, Soviet Mining Science, 9(2), 144-148.

Lilly, P.A., (1986). An empirical method of assessing rock mass blastability, The Aus. I.M.M./I.E. Aust. Newman Combined Group, Proc. Large Open Pit Mining Conference, pp. 89-92.

Napier-Munn et al (1996), Mineral comminution circuits, JKMRC Monograph Series in Mining and Mineral Processing 2, Ed. Napier-Munn, T.J.

Nielsen, K. and Kristiansen, J. (1995), Blasting and grinding – An integrated comminution system, EXPLO 95 Conference, AusIMM, Brisbane, September, PP 427-436.

Simkus R., and Dance A., (1998). Tracking hardness and size: Measuring and monitoring ROM ore properties at Highland valley copper, Proc. Mine to Mill Conf., Brisbane.

Scott, A., David, D., Alvarez, O., and Veloso, L., (1998), Managing fines generation in the blasting and crushing operations at Cerro Colorado Mine, Proc. Mine to Mill Conf., Brisbane.

Stagg, M.S., Otterness, R.E., and Siskind, D.E., (1992). Effects of Blasting Practices on Fragmentation, Proc. of the 33rd US Symp. on Rock Mechanics.

Valery, W. Development of an Advanced Model for the Cadia Hill Comminution Circuit (1999) – JKMRC Report submitted to Cadia Mines – Newcrest Mining