Figure 8. Cumulative distribution before and after implementation of the modified Kuz-Ram model in different rock types; Top: before modification; Bottom: after modification.

8 REFERENCES
cm. This is because of using a unique scale (two balls with 25 cm diameter) when taking the photographs from the blasted muck pile. Therefore when digitising the images by GoldSize software, the particles less than 25 cm were not completely designated. To overcome this obstacle, more photos were taken with different scales to cover all particles. To determine the size distribution of top magnetite rock in Figure 8, several scales were implemented to cover all sizes. It can be concluded from Figure 8 that the difference in estimation of fine particles by the Kuz-Ram model and data obtained from GoldSize software is the main source of the error of using unique scale in photos taken from blasted material for image analysis.

![Figure 7. Predicted X80 passing size after modification of n v/s actual 80% passing size.](image)

**7 CONCLUSIONS**

The Kuz-Ram fragmentation prediction model is the model most widely studied and recognised in mining industries. It has been quite successful due to the fact that it is simple and quick to calibrate and also easy to use. In this paper fragmentation results of image analysis and the Kuz-Ram prediction model were presented for three different materials in Gol-e-Gohar iron mine of Iran. Comparison of the cumulative size distribution of image analysis and the Kuz-Ram model shows that this model can predict the size distribution of blasted rock in Gol-e-Gohar mine, but it required some modification to calibrate the model. The investigation of fragmentation in different rock types indicates that with the same blasting pattern, various fragmentations will be obtained in a mine because of the variety of rock types and discontinuities. The only parameter in the Kuz-ram model that considers the physical and geotechnical properties of rock is the rock factor (Fr). To have a good estimation of the rock factor Monte Carlo simulation was used in order to determine the Fr for three different materials in Gol-e-Gohar iron ore mine. Because of the good correlation between the uniformity coefficients obtained from the Kuz-Ram model and the actual Gol-e-Gohar data, it is possible to “calibrate” a uniformity factor obtained from equation 4 using a factor to decrease the value calculated by the Kuz-Ram model (equation 5).

The results of model verification show that the modified Kuz-Ram model is able to predict rock fragmentation of blasted rock with an accuracy of 80 percent in Gol-e-Gohar iron ore mine.
Kuznetsov’s equation using Fr obtained from Monte Carlo simulation. Despite X50, 80% passing predicted have not a good correlation with the actual data as shown in Figure 4(B). The difference can be justified by the variety of the uniformity coefficient.

5.2 Uniformity Coefficient
The uniformity of fragmentation is expected to be fundamentally a function of pattern geometry, charging condition and rock mass characteristics. Literature indicates that the uniformity index for blasted rock masses generally lies between values of 0.6 and 2.2 (Chung et al, 2001). The larger the n value, the steeper the curve, i.e. the narrower the range of particle sizes in the given material. Values below 0.6 tend to indicate non-uniform breakage and fragmentation caused by the combination of blasting performance and other secondary effects such as structurally controlled failures, over break, back break and/or poor stemming performance (O Nederra et al, 2006).

Figure 5 shows the uniformity factor obtained from equation 4 versus the real uniformity in Gol-e-Gohar iron mine. As shown in Figure 5, equation 4 overestimates the uniformity factor. It is indicated from Figure 5 that the Rosin-Rammler equation tends to represent more uniform distribution but the size distribution in Gol-e-Gohar iron mine is not uniform due to less performance of drilling and blasting.

The scatter plot between predicted and actual uniformity factor, “n” in Figure 6, shows that there is a good correlation between them (r2 ≥ 80%). Therefore it is possible to “calibrate” a uniformity factor obtained from equation 4 using a factor to decrease the value calculated by the Kuz-Ram model. This factor is represented as below:

\[ n' = 5.3n - 7.8 \]  \hspace{1cm} (5)

Where n’ is the modified uniformity factor and n is the normal uniformity factor obtained from equation 4. The coefficient of determination in equation 5 (r2) is 0.89.

6 DISCUSSION
Using the modified uniformity factor, it is possible to have an accurate estimation of X80 in Gol-e-Gohar. Figure 7 compares the recorded X80 with the predicted value based on the modified Kuz-Ram model. Figure 8 represents the cumulative distribution of two different blasting patterns before and after implementation of the modified Kuz-Ram model. The cumulative size distribution in oxide rock shows that there is significant difference in real and predicted data in fine materials especially for the particle size less than 30.
Where \( Fr \) is rock factor (suggested 7 for medium rock; 10 for hard, highly fissured rock and 13 for very hard rock); \( Q(\text{kg}) \) is the quantity of explosive in a blast hole; \( V_0(\text{m}^3) \) is rock volume broken by a blast hole (burden \( \times \) spacing \( \times \) bench height); \( E \) is relative weight strength of explosive (ANFO=100; TNT=115 and Slurry= 117); \( R \) represents the percentage smaller than \( x \), \( x \) is rock size and \( n \) is the uniformity coefficient.

The rock factor is calculated from an equation originally developed by Lilly in 1986 for blastability index:

\[
Fr = 0.06(RMD + JF + RDI + HF) 
\]

Where, \( Fr \) is the rock factor as mentioned above, \( RMD \) is the rock mass description, \( JF \) is the joint factor, \( RDI \) is the rock density index and \( HF \) is the rock hardness factor.

Cunningham (1987) further developed an equation to estimate the uniformity coefficient \( n \) of the Rosin-Rammler distribution curve from blast design parameters:

\[
n = \left( \frac{2.2 - 14}{B} \right) \left( \frac{1 + S/B}{2} \right)^{0.5} \left( 1 - \frac{W}{B} \right) \left( \frac{L}{H} \right) 
\]

where \( B \) is the blasting burden (m), \( S \) the blast hole spacing (m), \( D \) the blast hole diameter (mm), \( W \) the standard deviation of drilling accuracy (m), \( L \) the total charge length (m) and \( H \) the bench height (m).

Widely accepted, this equation is the starting point of any mining operation linked to blasting. Because of this, high correlation and good prediction capacity is required. Available fragmentation data obtained from digital image analysis are used to examine whether the Kuz-Ram equation is satisfied. Figure 2(A) shows the 50% passing predicted by Kuznetsov’s equation against the actual size at Gol-e-Gohar. The comparison of actual X80 with the predicted value based on the Kuz-Ram model is also presented in Figure 2(B).

However, even though the Kuz-Ram model has been used widely for estimating blast fragmentation, it has some drawbacks. One of them is that the rock quality factor rating is based on subjective descriptions, such as massive, blocky or friable. With the same blasting pattern, various fragmentations will be obtained in a mine because of the variety of rock type and discontinuities. As represented by Figure 2, the Kuz-Ram model overestimates the particle size in top and bottom magnetite while for the oxide zone, the results of the Kuz-Ram model are less than the real size.

\[
R = 100 - e^{-0.693 \left( \frac{x}{x_{50}} \right)^{1.4}} 
\]
2 GOL-E-GOHAR IRON MINE

Gol-e-Gohar iron ore complex is located 56 km southwest of Sirjan in Kerman province and is situated on the Sanandaj-Sirjan metamorphic belt, which played an important role in the history of tectonics of the Iran plate margin. This deposit consists of 6 separated anomalies at a confine with 10 km approximate length and 4 km approximate width. More than 1.1 billion tonnes of iron ore reserves have made this area the largest iron ore deposit in Iran. Anomaly no 1 contains three zones (top magnetite, bottom magnetite and oxide) with a proven reserve of about 250 million tonnes and mineable reserve of 191 million tonnes. The annual production of this mine is 10.5 million tons (7 million tons of ore plus 3.5 million tons of overburden, waste and tailings). The iron grade in this mine is 55.9%. The drilling and blasting parameters of different rock types at Gol-e-Gohar iron mine is listed in Table 1.

3 SIZE DETERMINATION

The most popular method to quantify fragmentation is determination of size distribution using the digital image processing technique which is the second most reliable method after sieve analysis. In this method, images acquired from muck pile, haul truck, leach pile, draw point, waste dump, stockpile, conveyor belt, etc are delineated by using digital image processing techniques and size distribution of fragmented rocks is determined finally.

To estimate size distribution, images were taken from muck piles during loading. Having digitised images, the distribution of blasted rock was obtained by GoldSize software (Osanloo et al, 2005). The basic steps are sampling the photos, processing the images and obtaining the size distribution curve of the blasted material (Figure 1).

Random sampling is done from the whole set of images assigned to a blast. Photos with bad quality or poor lighting are rejected manually. In some blasts, more than half of the photos are eliminated according to these criteria. At least twenty photos per blast are selected for the analysis. Each photo contains a known object as scale. In the case of Gol-e-Gohar iron mine two balls of 25 cm diameter are used. Fragmentation results of image analysis of different rock types at Gol-e-Gohar are presented in Table 2. According to this study the first blast pattern produced the largest X80, with the least uniformity coefficient, whereby the uniformity coefficient of the last pattern (last row) is maximum as a result of its minimum X80.

Table 1. Drilling and blasting parameters of Gol-e-Gohar iron mine.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Rock Type</th>
<th>Top magnetite</th>
<th>Oxide</th>
<th>Bottom magnetite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock density (ton/m³)</td>
<td>4.37</td>
<td>3.92</td>
<td>4.15</td>
<td></td>
</tr>
<tr>
<td>Hole diameter (mm)</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Burden (m)</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Spacing (m)</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Bench height (m)</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Shot drilling (m)</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Stemming (m)</td>
<td>6</td>
<td>7.5</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>Weight of explosive (kg/hole)</td>
<td>508</td>
<td>441</td>
<td>485</td>
<td></td>
</tr>
<tr>
<td>Powder factor</td>
<td>1.2</td>
<td>0.6</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>Type of explosive</td>
<td>ANFO &amp; Slurry</td>
<td>ANFO</td>
<td>Slurry</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. Determination of rock size distribution using GoldSize software, A) Sampling the photos; B) Input images; C) Object contours; D) image processing result (Osanloo et al, 2005).

Table 2 –The results of rock size distribution in several blasted patterns in the mine.

<table>
<thead>
<tr>
<th>Blast no.</th>
<th>Rock type</th>
<th>X₅₀ (cm)</th>
<th>X₉₀ (cm)</th>
<th>Coefficient of Uniformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Oxide</td>
<td>48</td>
<td>114</td>
<td>0.80</td>
</tr>
<tr>
<td>2</td>
<td>Top magnetite</td>
<td>44</td>
<td>74</td>
<td>1.02</td>
</tr>
<tr>
<td>3</td>
<td>Oxide</td>
<td>31</td>
<td>77</td>
<td>1.05</td>
</tr>
<tr>
<td>4</td>
<td>Oxide</td>
<td>27</td>
<td>78</td>
<td>1.07</td>
</tr>
<tr>
<td>5</td>
<td>Overburden</td>
<td>20</td>
<td>60</td>
<td>1.09</td>
</tr>
<tr>
<td>6</td>
<td>Top magnetite</td>
<td>33</td>
<td>45</td>
<td>1.18</td>
</tr>
<tr>
<td>7</td>
<td>Oxide</td>
<td>26</td>
<td>98</td>
<td>1.23</td>
</tr>
<tr>
<td>8</td>
<td>Oxide</td>
<td>48</td>
<td>89</td>
<td>1.35</td>
</tr>
<tr>
<td>9</td>
<td>Oxide</td>
<td>26</td>
<td>52</td>
<td>1.54</td>
</tr>
<tr>
<td>10</td>
<td>Waste</td>
<td>27</td>
<td>54</td>
<td>1.83</td>
</tr>
<tr>
<td>11</td>
<td>Bottom magnetite</td>
<td>21</td>
<td>34</td>
<td>2.10</td>
</tr>
</tbody>
</table>

4 KUZ-RAM MODEL

The Kuz-Ram model is probably the most popular model to predict fragmentation of blasted rock mass. It was developed by Cunningham (1983) who modified Kuznetsov’s equation for ANFO-based explosive to estimate average fragmented size (X50) and combine it with the Rosin-Rammler equation to predict the entire size distribution. The equations are
Prediction of rock fragmentation at Gol-E-Gohar Iron mine based on a modified Kuz-Ram model

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1 INTRODUCTION
In any mining project, drilling and blasting are the first basic operations that form part of an integrated system. They can influence the result of the subsequent operations in productivity as well as in costs. The size distribution of a blasted muck pile can be used to evaluate the stability of a waste dump, to optimise loading cycle times and crushing cost. Therefore it is necessary to measure rock fragmentation in different stages of the mining process.

Several alternative procedures can be used to measure fragmentation. Methods of determining the size distribution of fragmented rock after blasting are grouped as direct and indirect methods. Sieving analysis of fragments is the only direct method. Although it is the most accurate technique compared to others, it is not practical because implementation of this method is expensive and time consuming (Franklin et al, 1996). For this reason, indirect methods, which are observational, as well as empirical and digital methods have been developed.

The most popular method to quantify fragmentation is determining the size distribution using digital image processing techniques. This method is cheap, consumes less time and does not interrupt production at site. Due to these reasons it is preferred widely by explosives engineers; moreover it is the second most reliable method after sieve analysis (Higgins et al, 1999). Several software suites such as SPLIT, WipFrag, GoldSize, FRAGSCAN, TUCIPS, CIAS, PowerSieve, IPACS, KTH, WIEP, etc are commercially available to quantify size distribution (Kemeny et al, 1999).

The other way to determine rock fragmentation is employing empirical models. A variety of modeling approaches ranging from purely empirical to rigorous numerical have been used to predict fragmentation from blasting. The most widely used model was developed by Claude Cunningham (1983), based on the size distribution curve of Rosin-Rammler and the average blast fragment size given by VM Kuznetsov (1973), who estimates the average fragment size, X50, based on explosive energy, powder factor and rock factor. Larsson (1973) proposed an equation to determine X50 with regards to drilling pattern, specific charge and rock properties.

Even though digital imaging processing techniques are cheap and accurate, empirical models are quite successful due to the fact that they are simple, quick to calibrate and very easy to use (Liu 2006). It is also possible to determine the drilling pattern to achieve appropriate fragmentation by applying empirical models. In this paper the Kuz-Ram model is modified based on the results of image analysis in Gol-e-Gohar Iron mine of Iran.