Arch. Min. Sci., Vol. 56 (2011), No 1, p. 119–134

Electronic version (in color) of this paper is available: http://mining.archives.pl

A. PARHIZKAR*, M. ATAEI**, P. MOAREFVAND***, V. RASOULI****

# GRADE UNCERTAINTY AND ITS IMPACT ON ORE GRADE RECONCILIATION BETWEEN THE RESOURCE MODEL AND THE MINE

# NIEPEWNOŚĆ ODNOŚNIE JAKOŚCI ZŁOŻA I JEJ WPŁYW NA ZGODNOŚĆ POMIĘDZY MODELOWANĄ I FAKTYCZNĄ JAKOŚCIĄ ZŁOŻA RUDY

Major differences between estimated grade and actual grade are a usual problem in many open pit mines. The estimated grade is predicted in exploration stage from data obtained from boreholes, whereas the actual grade would be determined only after the mining operation. The poor reconciliation between the values of estimated and actual grades can cause major economic losses to the mining industry. Many different factors affect the reconciliation process in a mining operation. The nature of the orebody, the random uncertainty and the systematic errors are three main sources affecting the reconciliation process in exploration stage of the orebody. In this paper each source of uncertainty is studied and a probabilistic model is presented to determine the role of each item in total uncertainty of the grade parameter. The model ability was investigated in the study of real data taken from an iron open pit mine in Iran. The results showed the systematic uncertainty, the nature of the orebody and the random uncertainty are the main causes of poor reconciliation in the case study respectively.

**Keywords:** grade, uncertainty, reconciliation, open pit

Poważne rozbieżności pomiędzy szacowaną a rzeczywistą jakością złóż rudy stanowią typowy problem w wielu kopalniach odkrywkowych. Szacowaną jakość określa się na etapie prac poszukiwawczych, na podstawie danych z otworów zaś rzeczywistą klasę złóż określić można jedynie w trakcie prac wydobywczych. Niewielka zgodność pomiędzy danymi szacunkowymi a rzeczywistymi powodować może znaczne straty finansowe dla sektora wydobywczego. Wiele rożnych czynników ma wpływ na poziom zgodności pomiędzy tymi danymi: charakter złoża rudy, niepewność losowa i błędy systemowe to trzy główne czynniki warunkujące poziom zgodności na etapie prac poszukiwawczych. W artykule tym zbadano te trzy główne źródła i zaproponowano model probabilistyczny dla określania roli poszczególnych

* DEPARTMENT OF MINING ENGINEERING, SCIENCE AND RESEARCH BRANCH, ISLAMIC AZAD UNIVERSITY, TEHRAN, IRAN

** DEPARTMENT OF MINING ENGINEERING, SHAHROOD UNIVERSITY, SHAHROOD, IRAN

*** DEPARTMENT OF MINING AND METALLURGICAL ENGINEERING, AMIRKABIR UNIVERSITY OF TECHNOLOGY, TEHRAN, IRAN

**** DEPARTMENT OF PETROLEUM ENGINEERING, CURTIN UNIVERSITY, PERTH, AUSTRALIA

czynników przyczyniających się do powstania niepewności odnośnie parametrów jakości złoża. Możliwości modelu przebadano na podstawie danych rzeczywistych uzyskanych z kopalni odkrywkowej rud żelaza w Iranie. Wyniki wskazują, że niepewność systemowa, charakter złoża i niepewność losowa w tej kolejności stanowią trzy główne czynniki warunkujące niewielki poziom zgodności pomiędzy danymi prognozowanymi a rzeczywistymi.

**Słowa kluczowe:** klasa złoża, niepewność, poziom zgodności, kopalnia odkrywkowa

# 1. Introduction

Reconciliation is a simple concept that is often difficult to apply. Ore grade reconciliation is a time-consuming process in a mining operation. Poor reconciliation may result in the long term in a pit being incorrectly optimized, in the medium term cash flow predictions may be disastrously inaccurate, and in the short term the allocation of ore and waste material by grade control may be wrong (Thomas & Snowden, 1990). For Canada and USA a World Bank survey showed that 73% of mining projects failed due to the problems in their ore reserve estimates, which led to a loss of US$1106 million in capital investment (Vallee, 2000; Dimitrakopoulos, 2007). Many efforts carry out in order to improve the estimation process such as optimization of additional exploratory boreholes (Soltani & Hezarkhani, 2009) but many different mines failed to estimate the ore grade accurately; it means the procedure of grade estimation in exploration stage has been unsuccessful (Burmister, 1988; Knoll, 1989; Clow, 1991). Rossi and Parker (1993) have shown 20 mines out of 39 mines failed to estimate the ore grade accurately. Similar reports have been published showing the impact of poor grade reconciliation on the economic condition of a mining company (Baker & Giacomo, 1998; Carrasco et al., 2004).Unfortunately large differences between reserve estimation and actual production are not unknown in the mining industry (Schofield, 2001). A complete reconciliation needs a complex system of data from various packages and databases (Morely, 2003). The results of such a complex system are used to define annual factors that can be applied to estimations to have a better reconciliation between the resource model and the mine production (for example Bischoff & Morely, 1993; Elliot et al, 1997; Pevely, 2001). Poor reconciliation, despite adequate grade control sampling and good geological control, causes irreparable disadvantages in many of open pit gold mines in Australia (Snowden, 2000). Fifty percent under estimation of ounces mined has been reported from Sunrise open pit gold mine (Haren & Williams, 2000). Very poor reconciliation was reported by Elliot et al. (2001) at McKinnons open pit gold mine for low grade materials. Burmister (1988) and Warren (1991) provide an analysis of reconciliation of 35 gold mines where there was an overestimation of the production grade by 58 percent in the worst case. Schofield (2001), Morely (2003) and Noppe (2004) have highlighted the importance of accurate and precise estimation of ore grade for different types of ore bodies.

The reconciliation process can be segregated into different stages (Crawford, 2003). The aim of this paper is to develop a probabilistic model to improve reconciliation between the exploration model and the mine. In this stage of reconciliation the model focuses on the factors fall in the exploration area, so the impact of factors related to mine or production phases on reconciliation process will not be considered.

# 2. The sources of grade uncertainty in exploration stage

Before presenting the probabilistic model, it is necessary to find the most important parameters which affect the reconciliation process in exploration stage and must be considered in the model. The major parameters in this area are introduced below.

## 2.1. The nature of the orebody

The natural variability of the orebody affects the estimation process of the ore grade. The nugget effect, in a variogram function, indicates the natural or inherent variability of the orebody. High natural variability can increase the amount of misclassification because deciding whether a block is ore or waste in a high nugget effect environment is too problematic.

## 2.2. Random uncertainty

The statistics of grade parameter are subject to uncertainty because of the insufficient number of field sampling. This type of uncertainty is called random or statistical uncertainty because its value decreases with increasing the number of samples.

## 2.3. Systematic errors

Limited number of samples causes the random uncertainty but there is another type of error which has no relationship with the number of samples. These errors exist because of differences between real (in situ) and laboratory conditions due to factors such as scale effect and anisotropy. The discrepancy between blasthole and borehole samples cannot be resolved by increasing the number of samples. This type of error is called systematic error. The study scale in grade estimation process differs from the scale in which the actual grade is measured due to the borehole`s diameter, in open pit mining method, being smaller than blasthole`s diameter and the borehole`s density being less than blasthole`s density. These are the sources of systematic errors which affects the accuracy of estimated grade and hence reconciliation process.

Studying the literature of reconciliation process shows that increasing the number of samples in order to improve reconciliation usually yields with no success (Thomas and Snowden, 1990; Snowden, 2000; Elliot et al., 2001). In particular, Magri and Ortiz (2000) have shown that the optimum classification of materials to ore and waste cannot be reached even using samples without errors.

# 3. The probabilistic model

Statistically, the best estimate of an unknown parameter is the mean or expected value and the uncertainties can be expressed in the form of variance or standard deviation or coefficient of variation (C.O.V.).

If the grade estimator considers the natural variability of the grade parameter then two correction factors will be needed to reconcile the estimated grade with actual grade. These correction factors must be applied to correct the statistical uncertainty and systematic errors. This can be written in the form of

$$G_a = C_r C_s G_e \tag{1}$$

Where $G_a$ and $G_e$ represent the actual and estimated grade, respectively and the natural variability is accounted for in estimated grade. $C_r$ and $C_s$ are the correction factors applied to rectify statistical and systematic errors, respectively.

Using first order uncertainty analysis model the mean value of actual grade can be calculated as

$$\bar{G}_a = \bar{C}_r \bar{C}_s \bar{G}_e \tag{2}$$

where the bars show the mean value of each parameter.

Also the uncertainty can be described as coefficient of variation which is the proportion of the standard deviation to the mean value and hence the C.O.V. is dimensionless. This parameter can be defined for actual grade as

$$CV_{G_a} \cong \sqrt{CV_{G_e}^2 + CV_{C_r}^2 + CV_{C_s}^2} \tag{3}$$

In this equation the $CV$s are the C.O.V. corresponding to each parameter.

For $n$ independent samples the mean value of estimated grade can be calculated as

$$\bar{G}_e = \frac{1}{n}\sum_{i=1}^{n} G_{e_i} \tag{4}$$

and the standard deviation of the estimated grade can be quantified as

$$S_{G_e} = \sqrt{\frac{\sum_{i=1}^{n}(G_{e_i} - \bar{G}_e)^2}{n-1}} \tag{5}$$

The uncertainty derived from inherent variability can be expressed as:

$$CV_{G_e} = \frac{S_{G_e}}{\bar{G}_e} \tag{6}$$

Base on central limit theorem (CLT) the distribution of $\bar{G}_e$ is normal and has a mean value and variance of $\mu$ and $\frac{S_{G_e}^2}{n}$, respectively. Here, $\mu$ is the average of the mean values in $n$ independent observations. The standard deviation of this distribution, called standard error of the mean value, can be calculated as

$$SE_{\bar{G}_e} = \frac{S_{G_e}}{\sqrt{n}} \tag{7}$$

where $SE_{\bar{G}_e}$ is the standard error of estimated grade.

The random uncertainty depends on statistical error which decreases with increasing number of samples. The C.O.V. for the correction factor of $C_r$ can be calculated as below:

$$CV_{C_r} = \frac{SE_{\bar{G}_e}}{\bar{G}_e} \tag{8}$$

The combination of equations 7 and 8 can be expressed as

$$CV_{C_r} = \frac{CV_{G_e}}{\sqrt{n}} \tag{9}$$

The mean value of $C_r$, $\bar{C}_r$, is taken as 1 because only random statistical error is considered.

The scale effect and anisotropy are the two major factors causing systematic errors affecting reconciliation process. The mean value of correction factor accounting for systematic uncertainty, $\bar{C}_s$, can be calculated as

$$\bar{C}_s = \prod_{i=1}^{m} \bar{C}_i \tag{10}$$

where $\bar{C}_i$ is the mean value of $C_i$s which are correction factors accounting for the $i^{\text{th}}$ systematic error.

The C.O.V. of $C_s$, $CV_{C_s}$, can be quantified as

$$CV_{C_s} = \sqrt{\sum_{i=1}^{m} CV_{C_i}^2} \tag{11}$$

where $CV_{C_i}$ is the C.O.V. of $C_i$.

There are two systematic errors affecting the reconciliation process and hence two correction factors would be required as $C_1$ and $C_2$ to account for scale effect and anisotropy, respectively. So equations 10 and 11 can be rewritten as

$$\bar{C}_s = \bar{C}_1 \bar{C}_2 \tag{12}$$

$$CV_{C_s} = \sqrt{CV_{C_1}^2 + CV_{C_2}^2} \tag{13}$$

The overall uncertainty of actual grade in the reconciliation process can be expressed as follows:

$$CV_{G_a} \cong \sqrt{\frac{S_{G_e}^2}{\bar{G}_e^2} + \frac{CV_{G_e}^2}{n} + CV_{C_1}^2 + CV_{C_2}^2} \tag{14}$$

The combination of equations 16 and 6 leads to

$$CV_{G_a} \cong \sqrt{\frac{S_{G_e}^2}{\bar{G}_e^2} + \frac{S_{G_e}^2}{n\bar{G}_e^2} + CV_{C_1}^2 + CV_{C_2}^2} \tag{15}$$

or

$$CV_{G_a} \cong \sqrt{\frac{(n+1)S_{G_e}^2}{n\bar{G}_e^2} + CV_{C_1}^2 + CV_{C_2}^2} \tag{16}$$

In order to quantify the uncertainty due to systematic errors the C.O.V. of each correction factor namely $C_1$ and $C_2$ must be determined. There are different methods to quantify the statistical parameters of these correction factors depending on available data set. If appropriate data at different scales, which demonstrates the scale and anisotropy effects, is available then the statistical parameters of the correction factors such as mean and C.O.V. can be calculated using simple statistical equations such as those presented before. In cases where there is no appropriate data but the range of each correction factor was specified then the required statistical parameters can be quantified using presented equations according to different distributions assumed for correction factors based on the experiences gained from experts (Ang & Tang, 1984). For example if the assumed distribution of $X$ is truncated normal distribution, then the mean value and C.O.V. of $X$ ($\bar{X}$ and $CV_X$) can be calculated from equations 17 and 18, respectively (See Figure 1) (Duzgun et al., 2002):

$$\bar{X} = \frac{1}{2}(X_l + X_u) \tag{17}$$

$$CV_X = \frac{1}{k}\left(\frac{X_u - X_l}{X_u + X_l}\right) \tag{18}$$

where $X_l$ and $X_u$ are the lower and upper limits of $X$ respectively.

The values of $CV_{C_1}$ and $CV_{C_2}$ needs to be determined in order to quantify the overall uncertainty. To estimate $CV_{C_1}$ which accounts for scale effect an isotropic area where the effect of anisotropy can be discarded would be needed. The estimation of $CV_{C_2}$ can be carried out after determination of the value of $CV_{C_1}$.

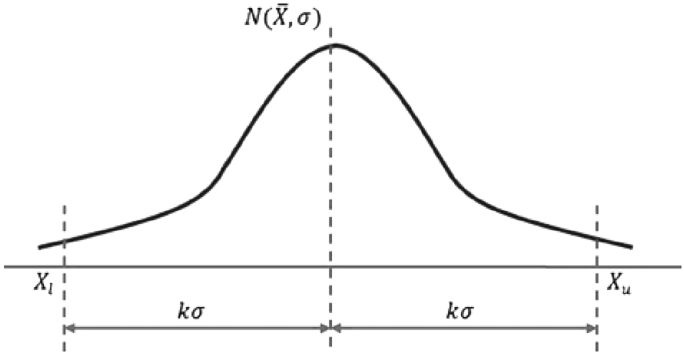


Fig. 1. Truncated normal distribution; $X_l$ and $X_u$ are the lower and upper limits of $X$ (Duzgun et al., 2002)

# 4. Case study

In this section the implementation of the proposed model in a real case study is presented. Chadormalou is a large iron deposit in Iran with 320 Mt of mineable reserve which is being mined using open pit mining method.

The block model dimension, which was constructed using Kriging estimator, is 25 m × 25 m × 15 m but the blastholes' pattern is 6 m × 7 m. Considering 3 m of subdrilling the blastholes' depth is 18 m.

## 4.1. Reconciliation condition in Chadormalou iron ore mine

In order to investigate the reconciliation condition in Chadormalou iron ore mine the reserve block model was used to compare the estimated grade with actual grade gathered from boreholes. Figure 2 shows the histograms of estimated and actual grades. Statistically, the structure of esti-

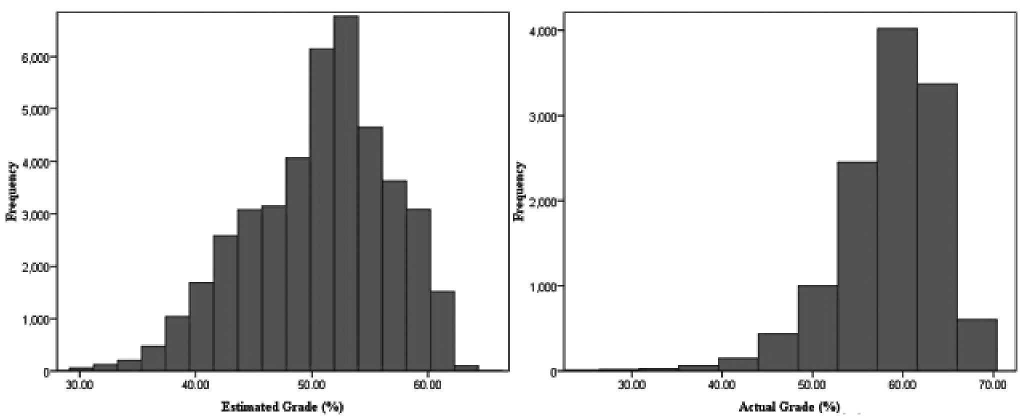


Fig. 2. Histograms of estimated grade and actual grade which demonstrate two different statistical populations

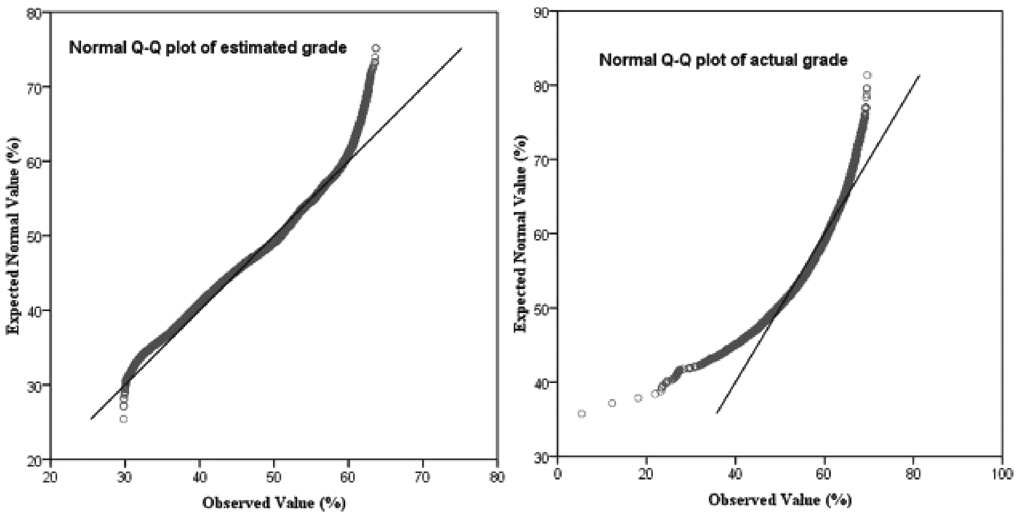


Fig. 3. Q-Q plots of estimated grade and actual grade

mated grade differs from the structure of actual grade in Chadormalou iron ore mine. The normal Q-Q plot of estimated and actual grades which is shown in Figure 3 confirms this subject.

Figure 4 shows a comparison between estimated and actual grade of Chadormalou iron ore mine. This Figure demonstrates the poor reconciliation between estimated grade, calculated using Kriging estimator, and the actual grade, comes from blastholes data. The mining process suffers from such low degree of reconciliation specially for the purpose of a precise mine planning and design.

Applying a cut-off grade of 55% to each axis the misclassification of exploited materials to ore and waste can be determined. This is shown in Figure 4 where most proportion of misclassification is seen to belong to ore materials sent to waste dump mistakenly. The Statistical parameters of estimated and actual grades can be seen in Table 1.

TABLE 1

Statistical parameters of estimated and actual grades

| Parameter | Min (%) | Max (%) | Mean (%) | Standard Deviation (%) |
|---|---|---|---|---|
| Estimated grade | 29.77 | 63.65 | 50.69 | 6.06 |
| Actual grade | 5.4 | 69.57 | 58.54 | 5.87 |

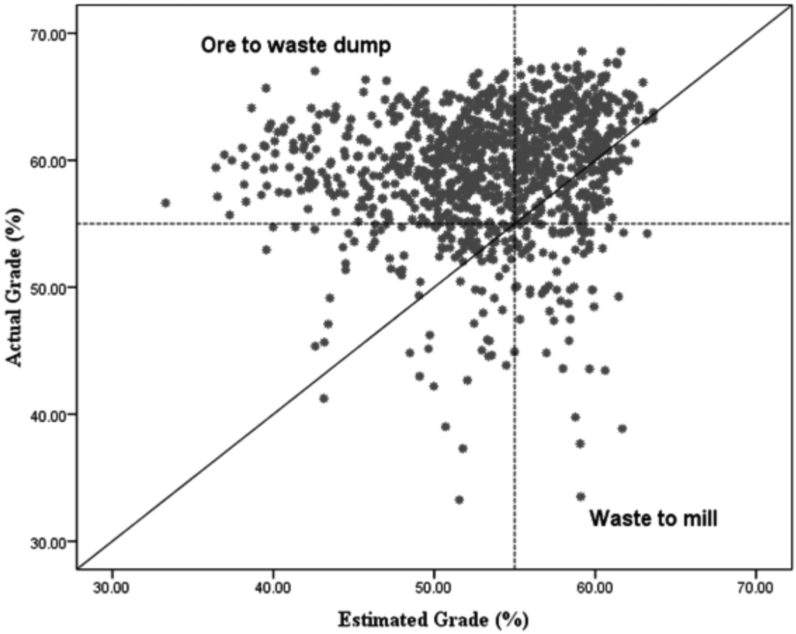


Fig. 4. Grade reconciliation condition in Chadormalou mine. The straight line indicates 1:1 slope. The dash lines show a cut off grade of 55% for each axis

## 4.2. Calculating grade uncertainty

In this section each source of uncertainty will be analyzed and the degree of their significance in overall uncertainty will be determined.

### 4.2.1. Natural variability

The mean value and standard deviation of estimated grade, $\overline{G}_e$ and $S_{G_e}$, calculated based on equations 4 and 5, as reported in Table 1, are equal to 50.69% and 6.06%, respectively. The statistics of estimated grade in Table 1 calculated from the whole data of reserve block model.

The C.O.V. of estimated grade from equation 6 equals

$$CV_{G_e} = \frac{6.06(\%)}{50.69(\%)} = 0.12$$

This value seems to be good for the purpose of orebody modeling as a mineral deposit with a C.O.V. less than around 0.5 and expectation of high tonnage may be usefully modeled with different estimation methods (Schofield, 2001).

### 4.2.2. Random uncertainty

The number of borehole samples used in estimation process is 2232. The statistical uncertainty which depends on the number of samples can be calculated from equation 9 as

$$CV_{C_r} = \frac{0.12}{\sqrt{2232}} = 2.54 \times 10^{-3}$$

### 4.2.3. Systematic errors

To quantify the systematic uncertainty it is necessary to determine the anisotropy exists in different area of the mine and then apply the required correction factors to remedy the sources of each systematic error such as scale effect and anisotropy. To calculate correction factors corresponding to scale effect one could consider an area with no anisotropy. This discards the anisotropy effect and therefore allows the scale effect on reconciliation process to be determined. Variogram, which represents the dispersion of variables, is a powerful function for studying anisotropy. The variogram maps were computed to distinguish the anisotropic areas of the Chadormalou deposit. As an example, variogram map corresponding to an anisotropic level of the deposit is shown in Figure 5.

The variogram map provides visual picture of variogram in every compass direction. This allows one to more easily find the appropriate principal axis for defining the anisotropic variogram model. A transect in any single direction is equivalent to the variogram in that direction.

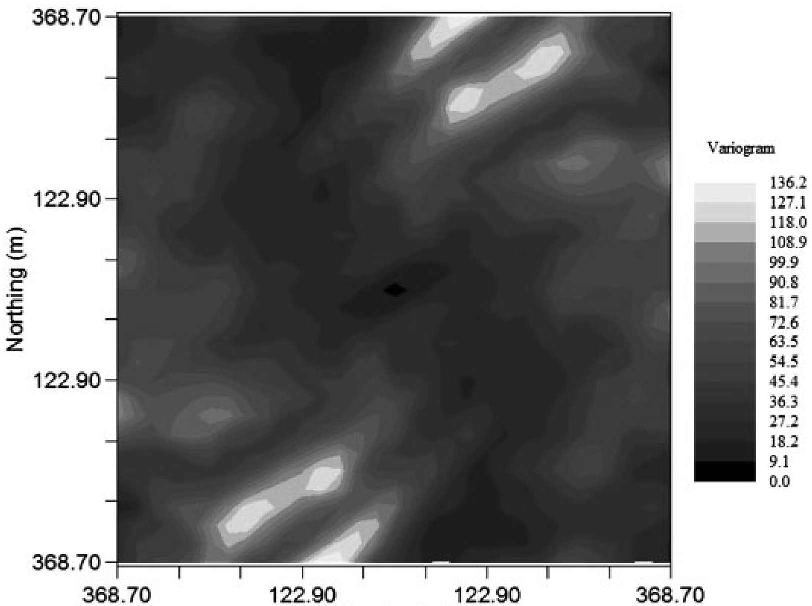


Fig. 5. Variogram map for level 1480 (m), Chadormalou iron ore mine

Table 2 shows the statistics of the correction factor accounting for scale effect, $C_1$, for the isotropic levels of the mine.

TABLE 2

The statistics of the correction factor accounting for scale effect ($C_1$)

| Range | Max | Min | C.O.V. | Standard deviation | Mean |
|---|---|---|---|---|---|
| 0.61 | 1.44 | 0.83 | 0.10 | 0.12 | 1.18 |

Table 3 shows the statistical parameters of estimated grade, actual grade and the correction factors for anisotropic levels of the mine.

TABLE 3

The statistical parameters related to anisotropic area of the mine

| Parameter | Estimated grade | Actual grade | Correction factor ($C_s$) |
|---|---|---|---|
| Mean | 54.80 | 52.07 | 1.01 |
| Variance | 4.49 | 54.04 | 0.02 |
| C.O.V. | 25.86 | 7.08 | 7.14 |

The correction factor in Table 3 accounts for both scale effect and anisotropy. It is now necessary to find the proportion of anisotropy in correction factor which was cited in Table 3. Equation 12 can be rewritten as

$$\bar{C}_2 = \frac{\bar{C}_s}{\bar{C}_1} \tag{19}$$

The mean value of $C_2$ accounting for anisotropy can be calculated from equation 22 as

$$\bar{C}_2 = \frac{1.01}{1.18} = 0.86$$

The variance of $C_2$ can be expressed as

$$S_{C_2}^2 = \frac{1}{\bar{C}_1^2} S_{C_s}^2 + \bar{C}_s^2 S_{\frac{1}{C_1}}^2 + 2\frac{\bar{C}_s}{\bar{C}_1} Cov\left(\frac{1}{C_1}, C_s\right) + S_{\frac{1}{C_1}}^2 S_{C_s}^2 + \left[Cov(\frac{1}{C_1}, C_s)\right]^2 \tag{20}$$

In equation 20 to calculate term $Cov(\frac{1}{C_1}, C_s)$ firstly the relationship between $\frac{1}{C_1}$ and $C_s$ must be determined. Figure 6 shows the best interpolated line and corresponding correlation equation. The denoted term can be quantified using the slope of the fitted line as

$$Fitted\ Line's\ Slope\ (FLS) = \frac{Cov(\frac{1}{C_1}, C_s)}{Var(\frac{1}{C_1})} \tag{21}$$

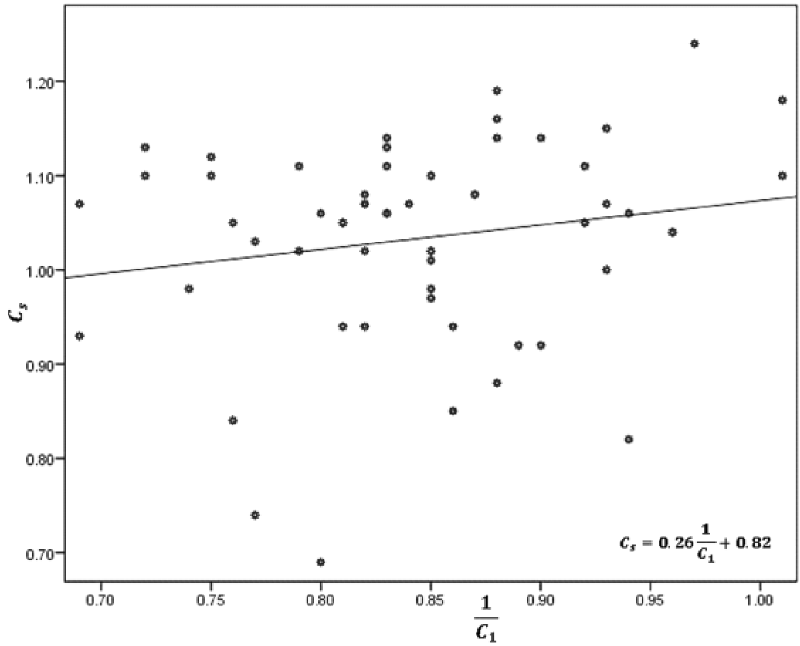


Fig. 6. The relationship between two correction factors $\frac{1}{C_1}$ and $C_s$

Or

$$Cov\left(\frac{1}{C_1}, C_s\right) = FLS \times Var(\frac{1}{C_1}) \tag{22}$$

The mean value and variance of $\frac{1}{C_1}$ are 0.85 and 0.01 respectively. Replacing the numerical values of each parameter in equation 25 yields to

$$Cov\left(\frac{1}{C_1}, C_s\right) = 0.26 \times 0.01 = 2.6 \times 10^{-3}$$

$C_{C_s}^2$ can be calculated using equation 20 discarding small numbers as

$$S_{C_2}^2 = \frac{0.02}{1.18^2} + (1.01^2 \times 0.01) + \frac{2 \times 1.01 \times 2.6 \times 10^{-3}}{1.18} = 0.03$$

Hence:

$$S_{C_2} = \sqrt{0.03} = 0.17$$

The C.O.V. of $C_2$ can be calculated as

$$CV_{C_2} = \frac{S_{C_2}}{\bar{C}_2} = \frac{0.17}{0.86} = 0.20$$

Now the uncertainty of actual grade can be calculated using equation 15. Replacing numerical values of parameters into equation 15 gives the C.O.V. of actual grade as

$$CV_{G_a} \cong \sqrt{\frac{6.06^2}{50.69^2} + \frac{0.12^2}{2232} + 0.10^2 + 0.20^2} = 0.25$$

This value presents the uncertainty of actual grade for the whole orebody.

### 4.2.4. Improving reconciliation

In order to analyze the impact of correction factors on improvement of grade estimation and hence the reconciliation process, each area with determined actual grade was considered. Variograghy analysis was down and for isotropic areas only a correction factor ($\bar{C}_1$) and for anisotropic areas two required correction factors ($\bar{C}_1$ and $\bar{C}_2$) were applied to the estimated grade in order to improve the reconciliation process due to scale effect and anisotropy. Figure 7 shows the new status of reconciliation for Chadormalou iron ore mine after applying correction factors.

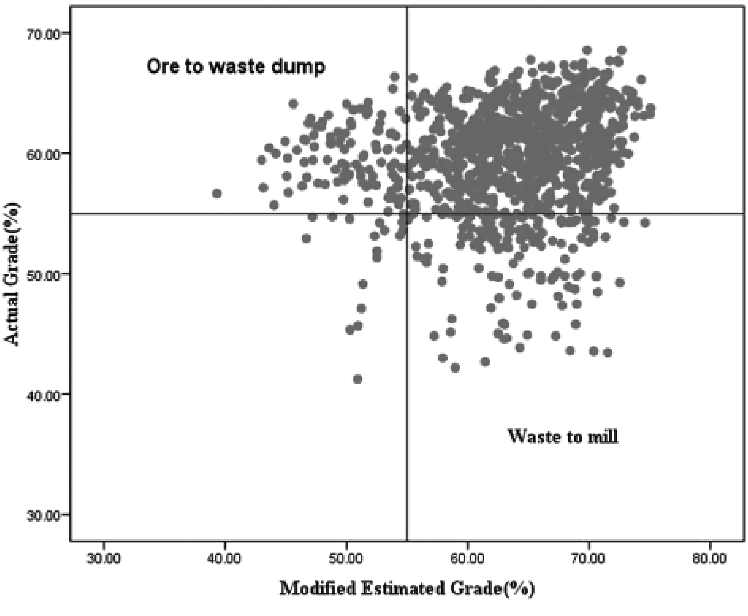


Fig. 7. Modified Estimated and actual grade after applying required correction factors for Chadormalou iron ore mine. The straight lines indicate a cut off grade of 55% for each axis

Comparison of Figures 4 and 7 shows applying the correction factors to remedy scale effect and anisotropy has improved the amount of reconciliation. To have a better comparison between Figures 4 and 7 and to see the effect of correction factors, an overlay scatter diagram was drawn to show the effect of correction factors on reconciliation process and the degree of misclassified materials to ore and waste in Chadormalou iron ore mine. Figure 8 shows the overlay scatter diagram.

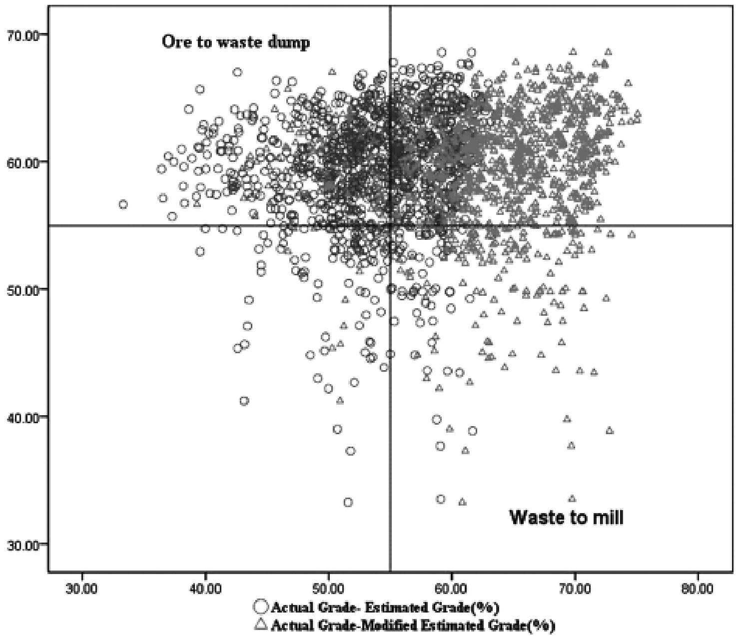


Fig. 8. The overlay scatter diagram of two pairs of data. The blue and red markers indicate actual-estimated grade and actual-modified estimated grade pairs respectively

Figure 8 shows applying the correction factors to estimated grade values can tangibly decrease the amount of ore materials sent to waste dump mistakenly. However a small increasing is seen in the amount of waste materials sent to mill due to applying the correction factors but this disadvantage, in compare with the gained excellence because of applying the correction factors, is small enough to be discarded. It is necessary to mention that the number of grade values used to calculate correction factors is negligible in compare with the grade values modified using these correction factors, hence a small set of reliable data would be enough to calculate the correction factors and remedy each source of uncertainty.

# 5. Conclusion

A probabilistic model was presented in this paper to quantify the ore grade uncertainty. The sources of uncertainty divided to three main parts namely natural variability, random uncertainty and systematic errors with respect to grade reconciliation process. This model can be used for every type of ore deposit but in this study the proposed model was applied in data taken from Chadormalou iron ore mine in Iran. The proportion of each source of uncertainty in decreasing the degree of reconciliation was calculated. The results indicated that the effective sources of uncertainty on reconciliation process in Chadormalou mine are systematic uncertainty, inherent variability and statistical uncertainty, respectively.

The natural variability of grade parameter was considered in grade estimator but for each type of other uncertainties a correction factor was considered to apply to estimated grade values to reconcile them with the actual grade values. The amount of reconciliation was improved by applying appropriate correction factors to the estimated grade values for Chadormalou iron ore mine.

## References


Thomas M., Snowden V., 1990. *Improving reconciliation and grade control by statistical and geostatistical analysis*. Strategies for grade control, AIG Bulletin 10, pp. 49-59.

Vallee M., 2000. *Mineral resource + engineering, economic and legal feasibility = ore reserve*. CIM Bulletin, Vol. 93, No. 1039, pp. 53-61.

Dimitrakopoulos R., Martinez L., Ramazan S., 2007. *A maximum upside/minimum downside approach to the traditional optimization of open pit mine design*. Journal of Mining Science, Vol. 43, No. 1.

Soltani S., Hezarkhani A., 2009. *Additional exploratory boreholes optimization based on three-dimensional model of ore deposit*. Arch. Min. Sci., Vol. 54, No 3, p. 495-506.

Burmeister B., 1988. *From resource to reality: A critical review of the achievements of new Australian gold mining projects during the period January 1983 to Septempber 1987*. Macquarie University.

Knoll K., 1989. *And now the bad news*. Northern miner magazine, Vol. 4, No. 6, p. 48-52.

Clow G., 1991. *Why gold mines fail*. Northern miner magazine, Vol. 2, No. 4, p. 31-34.

Rossi M., Parker H.M., 1993. *Estimating recoverable reserves – is it hopeless?* Geostatistics for the next Century, Montreal, Quebec, Canada, June 3-5.

Baker C.T., Giacomo S.M., 1998. *Resource and Reserve: their uses and abuses by the equity markets*. Ore reserve and Finance: A Joint Seminar between Australasian Institute of Mining and Metallurgy and ASX, Sydney.

Carrasco P., Carrasco P., Jara E., 2004. *The economic impact of correct sampling and analysis practices in the copper mining industry*. Chemometrics and intelligent laboratory systems Journal, pp. 209-213.

Schofield N.A., 2001. *The myth of mine reconciliation*. In Mineral Resource and Ore Reserve Estimation – The AusIMM Guide to Good Practice (Ed: A C Edwards), pp. 601-610 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Morley C., 2003. *Beyond Reconciliation – A Proactive Approach to Using Mining Data*. Fifth Large Open Pit Mining Conference, Kalgoorlie, WA, 3-5 November.

Bischoff K., Morley C., 1993. Geology*, resource definition and reserve estimation at Mount Charlotte*. Kalgoorlie, Western Australia, in Proceedings International Mine Geology Conference, pp. 1-17 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Elliot S.M., Snowden D.V., Bywater A., Standing C.A., Ryba A., 1997. *Reconciliation of the McKinnons Gold Deposit, Cobar, New South Wales*, in Proceedings Third International Mining Geology Conference, pp. 113-121 (The Australasian Institute of Mining and Metallurgy: Melbourne).

Pevely S., 2001, *Ore reserve, grade control and mine/mill reconciliation practices at McArthur River Mine*. The Australasian Institute of Mining and Metallurgy: Melbourne.

Snowden V., 2000. *Grade control and reconciliation*. Snowden Associates Pty Ltd, WEST PERTH.

Haren E., Williams P., 2000. *Mine geology practices at the Sunrise open pit*. 4th International Mining Geology Conference.

Elliot M.S., Snowden V., Bywater A. et al., 2001. *Reconciliation of the McKinnons gold deposit, Cobar, New South Wales*. The Australasian Institute of Mining and Metallurgy: Melbourne.

Warren M., 1991. *Pre-feasibility and feasibility studies: A case for improvements*. In Minopt 91, (The Australasian Institute of Mining and Metallurgy: Melbourne).

Noppe M., 2004. *Reconciliation: importance of good sampling and data QA-QC*. Mining and Resource Geology Symposium, XYZ, EGRU Contribution No.62.

Crawford D., 2003. *Reconciliation of reserves*. (Part 1), Pincock Perspectives, Colorado, ISSUE No. 49 – December 2003.

Magri E., Ortiz J., 2000. *Estimation of economic losses due to poor blast hole sampling in open pits*. WJ Kleingeld and Krige (eds), Geostats 2000, Cape Town, Document transformation technologies, Printed in South Africa.

Ang AH-S., Tang WH., 1984. *Probability concepts in engineering planning and design*. Vol. 2. New York: Wiley, pp. 333–400.

Duzgun H.S.B, Yucemen M.S., Kapruz C., 2002. *A probabilistic model for the assessment of uncertainties in the shear strength of rock discontinuities*. International journal of rock mechanics and mining sciences, p. 743-754.

*Received: 28 June 2010*