The Comparison Between Sequential Gaussian Simulation (SGS) of Choghart Ore Deposit and Geostatistical Estimation Through Ordinary Kriging

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Abstract: The most important properties of Geostatistical Simulations are, producing a group of images which shows a range of possible events, calculating probable percentage of happening and also determining the risk in each step of process. 137 holes have been drilled in this deposit. 3331 data from 125 drilled holes were gathered for grade estimation and reserve evaluation. Statistical studies indicated that Fe input data had single-population characteristics and obeyed a natural model. To carry out geostatistical studies, a spherical model was curve fitted over an empirical variogram. Plotting the empirical variogram in different directions showed neither geometric nor regional anisotropy for the deposit. For simulating via Sequential Gaussian Simulation (SGS) method, data were transferred to standard normal and then simulated 100 times (in this way 100 realizations were created). All of the realizations were honor to histogram and variogram of samples, so all realizations are valid. E_Type and probability maps are drawn in 12.5 meters intervals and grade-tonnage curves were drown for each realization. E_Type maps evaluate average 108 million tones for whole deposit. Grade-tonnage curves were showed the range of tonnage variance. That is between 97 and 116 million tones for whole deposit. To estimate the iron grade, Ordinary kriging method was used according to which, all of the exploitable blocks with dimensions 12.5*25*25 (m^3) were block estimated and results show the intact reserve of the exploited minerals was found to be 112 million tons of ore with an average iron grade of 56%.

Key words: Sequential Gaussian Simulation (SGS), Ordinary kriging, Choghart, Iron Ore Deposit, Realization, geostatistic

INTRODUCTION

I-1 Sequential Gaussian Simulation:

SGS is an algorithm which simulates nodes after each other sequentially, subsequently using simulated values as a conditioning data. It is necessary to use standard Gaussian values in SGS method, therefore the data are transformed into Gaussian space. The basic steps in SGS algorithm are listed below (Deustch, C. V., Journel, 1992):

1. calculate histogram of raw data, and statistical parameters
2. Transform data into Gaussian space.
3. Calculate and model variogram of Gaussian data.
4. Define a grid.
5. Choose a random path.
6. Krige a value at each nodes from all other values (known and simulated) and define Gaussian.
7. Draw a random value from Gaussian distribution which known as simulated value.
8. Simulate other nodes sequentially
9. Back transform simulated value (in this step a realization is generated)
10. To generate another realization, step 1 till 9 are repeated.

Variograms of transformed data are calculated and modeled. It is necessary to define a grid for simulation
and a random path to assess' grids nodes. According to the kriging mean and variance a Gaussian probability distribution is determined in each node. For estimating at each node it's necessary to choose a random path (Equation 1). A random value which is drawn from Gaussian probability distribution is known as a simulated value in each node. The basic steps in SGS algorithm are shown in fig 1. (Deustch, C.V., Journel, 1992)

\[ R_i = \text{mod}(5R_{i-1} + 1.2^n) - (5R_{i-1}) + 1 - \text{int}\left(\frac{5R_{i-1} + 1}{2^n}\right) 2^n \]  

(1)

Where: \( R_i \) is a random indicator for node i, \( m \) is a great number which makes \((2m)\) greater than number of network's nodes. (Gomez -Hernandez and Srivastava, Brately 1983)

Fig. 1: The basic steps in SGS algorithm (Deustch, C.V., Journel, 1992).

2- General Specifications of Study Area:
2-1 the Iron Areas of Iran:
Anarak-Bafq-Kerman Belt, which has almost 50 anomalies and 2 billion tones reserve, is the most important iron belt of Iran. Chadormalu Iron Ore Deposit with more than 400 million tones of iron ore (the largest explored deposit in Iran), Choghart Mines with more than 200 million tones of iron ore (the only supplier of Isfahan steel company) Esfordi Iron Ore Deposit, north anomaly of Narigan Mine, Saghand Iron Ore Deposit, Kalle-Siah Iron Ore Deposit, Se-Chahoon Iron Ore Deposit, Chah-Gaz Iron Ore Deposit and etc are some of the mines of this belt (Moor and Modabberi, 2003).
2-2 Specifications of Choghart District:
    Choghart mine is located 13 km northeast of Bafq and 120 km east of Yazd. Center longitude and latitude are $55^\circ:28^\prime:2^\prime\prime$ and $31^\circ:42^\prime:0^\prime\prime$ respectively. (Figure 2) As one of the first iron ore deposits, Choghart deposit has been regularly explored and exploited to supply the iron ore required for Zobe- Ahan factory of Isfahan (Asghari, 2003).

Fig. 2: Access routes to Choghart iron ore deposit and the anomalies around it.

3- Geology of Choghart Ore Body:
3-1- Petrology:
    Choghart deposit, and accumulation with a northwest - southwest orientation, is some 600m long and 200m wide. It can be seen on the ground surface and its thickness varies between 400 and 700m. A considerable diversity of various rocks like intrusive and metamorphous rocks pieces are seen around the deposit. The composition which forms deposit host rocks has two completely different and distinct appearances: 1- Rocks with a high percentage of Quartz and Feldspar named by geologists as Quartzite, Porphyry, Quartz and Granophyres 2- Rocks with a high percentage of Amphibolite which are of Actinolite, Trimolite and Feldspar types (Albite) as well as altered and amphibolitized alien rock pieces named as Amphibolite, Amphibiol, Pyroxenite, Hornblendeite and Metasmotite with different compositions. About 30 m of dark lime stone with many Calcite - filled joints were found in the holes bored for exploration in the northeast of Choghart (Moor and Modabberi, 2003).

3-2- Tectonic Settings:
    From the point of view of structural geology, three major types of structural features and faults have worked that indicate Pan African and Alpian events clearly. Pan African structures can be considered as the main agent and stimulator of ore concentration and the changes can be observed as intersecting north - east and east - west orientations (Fig. 3). In the regional scale (Samani 1988). These features are important in the formation of Magnetite - Apatite deposits. Alpine tectonic causes dynamo thermal alterations and revivals in faults whose results are alteration progress, chloritization and catalytic zones. Furthermore, Alpine faults give rise to displacements and brecciation in the deposit in the northwest -southeast orientations. (Samani, 1988)

3-3- Stratigraphy:
    The host rock of Choghart Ore Deposit is Morad series and Rizoo series are lying on top of that. Quaternary formations including pebble, gravel, soft sand and soil with some salts including gypsum and iron ore pebbles with thickness of 100-150 m are lying on the top of the iron formations. Choghart hill and its plain in 6 km of the mine belong to Mesozoic formations have 400-700 m thickness and are separated by Posht-e-Badam Fault (Samani, 1988).
3-4- Ore Deposit Genesis:

The genesis of Choghart Iron Ore Deposit and the other Oxidized Iron Ore Deposit in Bafq area is always struggled by geologists. It is because of less information about isotopic studies, fluid inclusion studies and confident analytical results. Generally some of the researchers believe on direct generation of magma, however, some others believe on metasomatic replacement of host rock by iron-rich hydrothermal fluid (Moor and Modabberi, 2003). Choghart apatite geochemical investigations showed, La/Lu ratio implies the segregation in upper magma. Negative anomaly of Eu shows the alkali-feldspathic rhyolit segregation in magma in near surface, however, the weak emptying of Ce may be a reason for metasomatic alteration in post-formation phase (Moor and Modabberi, 2003). Generally, Choghart Ore Deposit differs from Kirona Ore Deposit by two characteristics. First, the amount of rare-earth elements in Choghart is more than that in Kirona. Second, there is a big depletion of Ce with compared to Kirona, which is probably caused by metasomatic alteration of ore deposit after formation (Samani, 1988). In Choghart deposit, the main mineralization controlling factor is the boundary between metasomatites and its surrounded porphyritic quartz (Moor and Modabberi, 2003).

3-5- Ore Deposit Shape and Dispersion of Different Ores in Choghart Ore Deposit:

Geometrically point of view, the ore deposit could be compared to an ellipsoid with high slope. In an 800 meter NW-SE cross-section, the thickness of ore deposit in center regions exceeds to about 225-275 m. It should be mentioned that, with increasing the depth of the NW part of the ore deposit, its dip and direction will not be changed, but the direction of NE part, which’s direction is NW-SE in the surface, in 755 level will be changed to NE-SW (Moor and Modabberi, 2003).
3-6- the Quality of Choghart Ore, Side and Host Rocks:

The main Choghart minerals are magnetite, hematite (martite), apatite, tremolite and sometimes pyrite and albite. Based on mineralogical compositions, the different kinds of the ore could be classified as follow:

A. magnetitic ore
B. magnetite-martitic ore
C. magnetite-apatitic ore
D. magnetite-pyritic ore
E. magnetite-silicitic ore

magnetitic ore or “a” ore type is the most abundant. This ore has massive to grain texture, with mostly fine-grained shape (Asghari, 2003).

3-7- Different Types of Choghart Iron Ore:

Based on previous studies and documents, the different types of Choghart Iron Ore are (Asghari, 2003)
1. High-grade ore, non-oxidized and low phosphor
2. High-grade ore, oxidized and low phosphor
3. High-grade ore, non-oxidized and high phosphor
4. High-grade ore, oxidized and high phosphor. Also low-grade ore is classified to low phosphor and high phosphor ore (Asghari, 2003).

4- Alteration:

Host rock alteration could be divided into three different types namely alteration before ore formation, alteration simultaneous to ore formation and alteration after ore formation. Albitization, Fledespatization are among the mentionable characteristics of the deposit and some minerals such as Flogopite, Amphibolite, Scapolith, Chlorite, and Serpantine are abundant in this deposit. (Samani, 1988).

5- Available Data:

A number of 137 vertical and oblique holes in an irregular boring network were bored in the choghart deposit domain. 12 out of 137 holes did not cut through any minerals, thus the calculations of geostatistical simulation were made based on the data gained from 125 holes. Because of specimens had not equal length, decided to make equal composites. At first, a length histogram of the analyzed specimens was plotted. According to which, 1517 4-meter-long specimens out of 3331 overall data (45%) and 1100 2-meter-long specimens (33%) had the highest abundance. Thus it was decided that according to equation one, 2-meter-long composites be provided. Afterwards, 6185 new data were obtained for the considered regional variable (Fe) (Asghari, 2003).

\[ G_i = \frac{\sum L \times G_p}{\sum L} \text{, } \sum L = 2m \quad (2) \]

Where \( G \) is an equivalent grade obtained from making composites, \( L \) is the analyzed core length and \( G_p \) is the grade of the primary specimen (Hassani Pak and Sharafodin, 2002).

125 drill holes include 6185 data were used to Sequential Gaussian Simulation. Statistical analysis was performed for Fe values. This includes the estimation of basic statistic involving the mean, median, standard deviation, skewness and kurtosis. Statistical studies shown that Fe distribution is not highly skewed (fig. 4). The first step in SGS method is transferring data into standard normal distribution. Figure 5 shows histogram of transferred data.

For simulation through Sequential Gaussian method, it’s necessary to transfer data into Normal Standard distribution. This distribution has variance 1, Standard deviation 1, skewness 0, kurtosis 3 and means0. Fig. 5 shows Histograms of transferred data into Normal Standard distribution.
Fig. 4: Frequency distribution chart and statistical parameters of Fe. As shown, Fe input data had single-population characteristics and approximately obeyed a natural model.

![Frequency Distribution Chart of Fe](image1)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>52.6</td>
</tr>
<tr>
<td>Median</td>
<td>60.93</td>
</tr>
<tr>
<td>Mode</td>
<td>64.6</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>19.91</td>
</tr>
<tr>
<td>Skewness</td>
<td>1.12</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>2.67</td>
</tr>
<tr>
<td>Minimum</td>
<td>25.2</td>
</tr>
<tr>
<td>Maximum</td>
<td>70.3</td>
</tr>
<tr>
<td>Count</td>
<td>6165</td>
</tr>
</tbody>
</table>

Fig. 5: Histogram of transferred data into standard normal distribution.

![Normal Standard Distribution Chart of Fe](image2)

6- Variography:
6-1 - Variogram Modeling:

Geostatistical estimations are based on the existence of a spatial structure in the data, and variogram is the most important means of showing the spatial coherence of the data (Michel 1982). To plot the 3-dimensional variogram, the data in composite forms of uniform 2-meter length were used and estimated lag (distance between pairs of Points) of 40 meters was assumed. Two series of nondirectional and directional spherical model variograms were surveyed and plotted for the regional Fe variable (Fig. 6). Non directional Variogram is defined with Azimuth and dip equal to 0 and tolerance equal to 90 degree, while directional variogram has identified Azimuth and dip and tolerance is less than 90 degree. Specifications of these changes are mentioned in table 1. Equation (3) was used to calculate the variogram for different values (Journel and Huijbregts, 1978).
Variography was done in different directions (0, 45, 90, 135 azimuths) and different dips (0, 45, -45, 90) with a tolerance of 22.5° to survey the deposit isotropy. Neither regional nor geometric anisotropy was noticed after analyzing over 30 variograms, since in most variograms nearly the same ranges (270 to 315 meters) and similar sills (300 to 320 m) were obtained. Hence, to estimate each block, instead of using anisotropy ellipsoid a sphere was used. (Table 1)

Table 1: Specifications of directional and nondirectional 3-dimensional variograms

<table>
<thead>
<tr>
<th>Variogram Model</th>
<th>Azimuth</th>
<th>Dip</th>
<th>Tolerance</th>
<th>Sill(%)</th>
<th>Nugget Effect(%)</th>
<th>Range(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Spherical</td>
<td>0</td>
<td>45</td>
<td>22.5</td>
<td>315</td>
<td>125</td>
</tr>
<tr>
<td>2</td>
<td>Spherical</td>
<td>45</td>
<td>45</td>
<td>22.5</td>
<td>285</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td>Spherical</td>
<td>90</td>
<td>45</td>
<td>22.5</td>
<td>270</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>Spherical</td>
<td>135</td>
<td>45</td>
<td>22.5</td>
<td>308</td>
<td>122</td>
</tr>
<tr>
<td>5</td>
<td>Spherical</td>
<td>Directionless</td>
<td>Directionless</td>
<td>22.5</td>
<td>280</td>
<td>124</td>
</tr>
</tbody>
</table>

Kriging is a geostatistical estimation method known as the best linear unbiased estimator. In addition to having the lowest estimation variance, this linear estimation guarantees the estimations to be unbiased, provided the selected regional variable is normally distributed (Webster and Oliver, 2000). To estimate the deposit grade, block kriging should be used in which the relationship between the block to be estimated and the data is considered. Blocks were considered based on deposit exploitation conditions i.e. steps with height and width dimensions of 12.5*25*25m³.

7-1- Determining the Parameters of Estimation:

To make geostatistical estimation, the estimation parameters should be selected based on data distribution, the spatial structure and the model of variogram. The parameters used to estimate Choghart deposit are explained in the following section.

A- The Search Radius:

The search radius is usually \( \frac{2}{3} \) of the range of variogram i.e. 67%*280=167m.

But in this study, a lower value was assumed for it, firstly to avoid the result smoothing effect and secondly, due to the great number of data within the domain of the search radius reaching 4000 data in some case. Taking notice of the considerations above and bearing in mind that the deposit is isotropic, equal search radius of 120 m were assumed in X, Y and Z directions.
B- The Specifications of the Variogram:
The specifications of 3-dimensional, nondirectional variogram for the deposit have been mentioned in table 1.

C- Block Dimensions:
Taking into account the exploitation conditions of the deposit including the height and width of the exploitation benches, optimized dimensions of 25*25*12.5m were assumed for the blocks to be estimated.

D - the Minimum and Maximum Number of Points Used for Estimation:
The minimum and maximum number of points used, affect the estimation in two ways: 1- The more points participate in calculating the average, the more evident the smoothing effect will be 2- Under the same conditions, if fewer points are used to make the estimation, the error will increase. Thus, applying trial and error method in changing the number of points involved in the estimation of each block, 70 and 30 were selected as the maximum and minimum number of points, respectively.

8- Simulation:
To construct three-dimensional model, the deposit should be divided into 26 layers vertically with 12.5 meter thickness, then in each layer a number of 25*25 (m²) horizontal cells created. Gslib software (Deustch and Journel, 1992) used for simulation of deposit. Hence, to estimate each block of an image, instead of using anisotropy ellipsoid a sphere with a radius equal to range i.e.280 m was used. Finally the simulated values of Fe generated for 6693 cells. 100 realizations generated using SGS algorithm. Fig. 7 shows 4 plans of these realizations.

Fig. 7: Simulated blocks of level 1150 in 4 realizations (33, 46, 62, 78).

9- Validation of Results :
Validation of results is done by making a comparison between histogram and variogram of raw data and simulated values. Fig. 8 shows histograms and statistical parameters of 4 realizations. As shown in tables, there is a close match between raw data and realizations. On the other hand of raw data and realizations illustrated in Fig. 9 and Fig. 10 indicates respectively the reproduction of the variogram of raw data.
Fig. 8: Histogram and statistical description of Realizations 33, 46, 62 and 87.

Fig. 9: 3D Non directional Variogram of Simulated Fe

Fig. 9: 3D Non directional Variogram of Realizations 33, 46, 62 and 87. This figure shows that all realizations have similar spatial behavior.
One of the goals of Choghart mine simulation was to obtain ore reserve and trends of ore and waste. E_TYPE map is a map which resulted from average of realizations. As E_TYPE map is average 100 realizations so it is similar to kriging map (Deustch and Journel, 1992). Fig 11-a is a Kriged plan and b is an E_Type plan of level1150 (m) of deposit. As shown results of estimation through simulation and kriging are too much the same. According to this map low grade and high grade zones are continues. E_Type plan maps are calculated for reserve and 108 million tones with 45 % (Fe) cut off ore reserve estimated.

Probability maps are the most important result of simulation which denotes the probability of exceeding a threshold. This map generates by counting of number of grades exceeding a threshold in all images (realizations). Fig.12, is a map generated from the combination of 100 conditional simulations, and shows the probability of exceeding the 45%Fe grade in a plan. According to this map, the probability of exceeding a threshold (cut off = 45% Fe) is obtain. From these maps, some relevant information can directly use in mine planning. For example, the boundary between ore and waste will be defined.
12- Grade Tonnage Curves:

Grade tonnage curves are such as tools which guide mine managers in scheduling of production. According to this curve of cut off grade, average grade and tonnage of reserve can be estimated all together. In simulation there is a grade tonnage curve which corresponded to a realization, so several grade tonnage curves are drawn. The curve provides the uncertainty of potential Fe when analyzing cash flows and other financial aspects in evaluation of project. For calculating tonnage of each block, grade of each of each block, density and core recovery is needed. Fig. 13 is grade tonnage curve of deposit. It is illustrated that by increasing cut off grades, the tonnage is decreasing and average grade increasing. According to these curves the range of tonnage is gain. Suppose that the average grade is equal to 55.4% and cut off grade is 45% as portrait in fig. 12. These results can be used in optimization of excavation scheduling. (Vann, Bertoli and Jackson, 2002)

13- Conclusion:

The three dimensional deposit models were generated for Choghart mine using SGS algorithm. These models consist of over 6693 cells which reflect the heterogeneity of Fe. Simulated results reproduced the histogram and variogram of raw data indicate the validation of results. According to the 100 realization E_Type are created which reflect trends of ore and waste in deposit. Probability maps are the most important result of simulation which denotes the probability of exceeding a threshold. In this study 26 probability map for all levels of Choghart deposit is generated. Base on these maps, the boundary of waste blocks could be found. Grade-tonnage curves are used for prediction of mining production and risk assessment (Dimitrakopoulos, and Fonseca, 2003) because according to these curves the best and the worst alternatives
are produced, so the risk of operation is predictable (Vann, Bertoli and Jackson, 2002). Based on Sequential Gaussian Simulations (E_Type Maps), the Choghart Iron Ore deposit is containing of 108 million tones with average grade of 55.4% Fe and cut off grade is 45%. Grade-tonnage curves were showed the range of tonnage variance. That is between 97 and 116 million tones for whole deposit, while based on Ordinary block Kriging, results show the intact reserve of the exploited minerals was found to be 112 million tons of ore with an average iron grade of 56%. As told before, results of estimation through simulation and kriging are too much the same.

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