Geostatistical estimation analysis of typical Carlin gold deposit in Hunan province, China

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Abstract. In this paper, 3D mining modelling software was used to construct the 3D geological model of Typical Carlin gold deposit in Hunan province of China, and the geostatistics theories are also involved for the resource estimation which offer references for additional exploration and mining plans. Access database was constructed for gold deposit, topo DTM, mineralised body models and grade models are constructed by Surpac, and also analysis of the spatial grade distribution in reality was completed with statistic softwares. By using of geostatistics, assay samples are composited and analysed statistically and outliers influence was reduced to certain level. Experimental Variation functions were constructed for the strike, dip and vertical directions. Certain attributes are estimated by Ordinary Kriging estimation method. Comparing to the traditional estimation methods, estimation under 3D block model can obtain more reliable analysis results, which have significant reference values for dynamic management of mine operation.

1. Introduction

Geostatistics is one subject with regionalized variables as basis and the variability are always used as research tools for project analysis. Matheron (One famous French statistician) first put forward the concept of geostatistics with his research outcomes Traité de géostatistique appliquée [1]. Variation function is often used as the major research tool for analysis when the researchers are trying to analyze and summary the distribution characteristics of different variables [2-3]. Three-dimensional geological models can be used by related field researchers to understand the geological characteristics of the area more intuitively and clearly.

In this paper, a three-dimensional model of a typical Carlin gold deposit in Hunan Province was created by using Surpac 3D modelling and estimation software, and the independent grade distribution characteristics were analyzed. The Ordinary Kriging method (OK) based on Geostatistics theory is chosen for estimation based on original data. The parameters for estimation were optimized and the final 3D model grade estimation was completed which can also provide technical support for mining activities.

2. Model building and resource evaluation

2.1. Database building
The process of building the database mainly includes exploration information collecting in the mineralized areas. Geological data include the results of trenches, drill holes and surface pits. The distribution of lithology and faults can be recorded by geological logging procedures, and then the verified data can be imported into Surpac database module to construct a proper format of three-dimensional geological database. By using geological database to store geological information, the three-dimensional geological model can be established more accurately and comprehensively, which lays a foundation for subsequent resource evaluation. The author collected geological data of 151 boreholes from the research area, and establishes four basic tables: collar table, survey table, assay table and lithology tables. Among them, drill collar table mainly includes drill hole collar coordinates, drill hole depth, drill hole type, drilling time and drilling path; survey table mainly includes drill hole orientation and inclination and inclination depth; assay table mainly includes original core or pulp sample analysis results (including gold and other elements grade information); lithology table mainly includes information of rock type, stratum, mineral and alteration. After that, the established geological database is validated by three-dimensional software, and the DTMs and 3DMs are established in Surpac software based on proper interpretation methods.

2.2. Sample composting and Variation function analysis

2.2.1. Sample composting

Geological statistical analysis of database data and estimation of block model by sample grade or body weight require that every sample has the same weighting which means that all the sample should have the same sampling lengths. Thus, the analysis results are assured in the reasonable estimation process. Therefore, before the basic statistical analysis and variance function analysis of samples, it is necessary to commence samples composting. There are few different sample combination methods which include along the borehole direction composting method, bench composting method, geological domain composting method, ore body internal composting method and so on. For this paper, the method of composting along drilling direction with geological region method is adopted. In the process of sample composition, the influence of the average lengths of original samples, exploration lines spacings, minimum mining unit (MMU) and block model size are all considered for determination of final composting lengths\cite{4,5}.

The gold mineralisation wireframe ("domain") is used to code the constructed database to identify the main mineralisation intersections. The most common lengths of the sample in the mineralised wire frame is 2 meters, so that 2 meters is chosen as the common statistical analysis composite length for all the samples, and Surpac software is used to extract the original sample data and create the final composited files. After basic sample composition, statistical analysis of gold data was carried out by supervisor statistical software. The analysis results show that the composited samples results are still highly consistent with the lognormal distribution (Figure. 1 a, Figure. 1 b), which indicate that the gold grades can still be considered as random continuous variable after sample composition. This provides a precondition for experimental semi - Variation function analysis. Based on simple statistical analysis results which can reflect the overall mineralized domains characteristics, but it is still not good at reflecting the changes of samples in local scope and specific direction (strike direction, dip direction and vertical direction). It is a best method to solve the subject of local geology characteristics analysis by composting samples, analyzing the semi - Variation function of the processed combination results.
2.2.2. Variation function analysis

For describing the variability of samples grade distribution in selected deposits, most of time we use the average values, maximum values, variance values and standard deviation values of samples as common statistical analysis tools, which can be only used to summarize the basic information of the original data. The global values of these parameters do not always reflect the changes of samples along certain directions. Introducing experimental variation map into geostatistics are very useful to find out the actual randomness and correlation of regionalized variables, especially for the randomness of grades, to guide the definition of regionalized variables structures. Because the variable spatial distribution of mineralised bodies in different directions is often not identical which is also called spatial anisotropy, regionalized variables can be used to characterize mines changing with several major, semi-major and minor directions.

During analyzing and calculating the experimental semi-Variation function, the main extended direction of mineralization, secondary extended direction and the third extended direction will be analyzed. Assuming that the regionalized variable satisfies the second-order stationary hypothesis and intrinsic hypothesis, and there exist variation function and covariance function. Referring to the basic concept of geostatistics, the formula of variation function is as below:

\[
\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (Z(x_i) - Z(x_i + h))^2
\]  

(1)

In formula (1), \(N(h)\) is the size of step, \(h\) is The number pairs of data; \(Z(x)\) with \(Z(x + h)\) is two-point sample values which have distance of \(h\). Because the variation function is a statistical analysis method, more samples need be taken to obtain more robust analysis results.

When running a Simple Kriging estimation method, we assume that the average values of the all domains are known, but the average values for all samples are difficult to be located directly in reality, unless the average values of the known sample points are used to indicate the overall mineralized domains. The Ordinary Kriging estimation method does not rely on the mathematical expectation that the random variable \(Z(x)\) is known for all \(x\). The OK estimation method’s popular formula is as below:

\[
Z'(x) = \sum_{i=1}^{n} \lambda_i Z(x_i)
\]

(2)

In formula (2) \(Z(x)\) is the sample value, \(Z'(x)\) is the estimated value, \(\lambda_i\) is a weight coefficient, indicating the contribution extent of sample value \(Z(x_i)\) to estimated value \(Z'(x)\) at a specific spatial sample point \(x_i\).

For calculating the weight coefficient \(\lambda_i\) in the case that the two conditions of unbiased estimation and optimized estimation are both obtained, the calculation is based on the Lagrangian principle, and then the Kriging equation (3) is as below:
\[
\sum_{i=1}^{n} \lambda_i c(x_i, x) - \mu = c(x, x) \\
\sum_{i=1}^{n} \lambda_i = 1
\]  

(3)

In formula (3) \( c(x_i, x_j) \) , \( c(x_i, x) \) are covariances, \( \mu \) is the Lagrange multiplier.

We can determine the weight coefficient by deducing the above linear equations \( \lambda_i \) and Lagrangian coefficient \( u \), and then substitute to the following formula (4), so that we can obtain the Kriging estimated variance

\[
\sigma_k^2 = c(x, x) - \sum_{i=1}^{n} \lambda_i c(x_i, x) + \mu
\]  

(4)

In formula (4), \( c(x_i, x_j) \), \( c(x_i, x) \) are covariances, and \( \mu \) is the Lagrange multiplier.

In this paper, we used a spherical model as a variance function model to analyze all original data. The standard formula of the typical spherical model is as below:

\[
\gamma(h) = \begin{cases} 
\frac{3}{2a}h - \frac{1}{2}h^2 & h \leq a \\
1 & h > a
\end{cases}
\]  

(5)

In equation (5), \( a \) is the range and \( h \) is the line distance between two selected samples.

In the analysis process, the main dominated ore body 6 was selected as the main research object for variance function analysis and parameter determination. According to the basic geostatistics theory, the logarithm of samples are selected, and downhole directions which contain the most sample pairs are determined within a certain search radius, and then the nugget values are determined. The underground direction is basically vertical to the plane determined by the major mineralisation directions (which is considered as reasonable based on the initial exploration design). Variance function is the most important research tool in geostatistics. When it is used for structural analysis of regionalized variables or for any interpolation processing method, the variation function maps obtained in the first direction must be in several main directions. The curve fitting step was carried out (Fig. 2). Based on the theoretical variation function model, the variation function model which is used in the omni-directional evaluation calculation of mineralised body is finally determined, and its parameters (range, sill, nugget, etc.) are all determined with proper analysis.

In this research process, the variation function of gold grade is fitted and calculated according to the strike direction, dip direction and vertical direction of gold deposit. The calculation results are shown as below Table 1.

![Figure 2. Variation function distribution map](image-url)
2.2.3. Variation function validation

The reasonableness and correctness of grade evaluation results are verified by using the reasonableness verification procedure and the parameters fitted by the curve of variation function. Firstly, the estimated results of each domain are compared with the inverse distance (IDW) method and the composited samples’ average grades. The comparison results are shown in below Table 2. According to the statistical results, the estimation results are very stable, and the actual estimation errors for the selected analysis domain are within 5%.

Meanwhile, after completing the macro comparison of the estimated results of each mining section, the deviation between the grade value of each mining section and the true value is drawn, and the differences and changes are analyzed statistically, as shown in Figure 3 (X, Z direction). The validation plots show good correlation between the composite grades and the block model grades for the comparison by easting and elevation. The trends shown by the raw data are honoured by the block model. The IDW estimate compares well with the OK estimate. The comparisons show the effect of the interpolation, which results in smoothing of the block grades, compared to the composite grades.

| Zone       | Domain | Element | Nugget | Structure 1 C1 | A1 | Semi1 | Minor1 | Structure 2 C2 | A2 | Semi2 | Minor2 |
|------------|--------|---------|--------|---------------|----|-------|--------|---------------|----|-------|--------|
| Gold Domain| All areas | Au      | 0.21   | 0.7           | 29 | 1.2   | 1.6    | 0.1           | 142| 3.5   | 6.5    |

Table 1. Variation function analysis results table

Table 2. Resource Block Model Verification Table

| Domain | Object | Wireframe | Volume | Resource | Volume | Estimated | Volume | Resource | Estimated | Au | Number of Comps | g/t | g/t | comp vol | comp_Au |
|--------|--------|-----------|--------|----------|--------|-----------|--------|----------|-----------|----|----------------|-----|-----|----------|--------|
| 1      | 13,289 | 13,406    | 13,406 | 2.15     | 8      | 2.34      | 8      | 2.34     | 0.88      | -8 |                 |     |     |          |        |
| 2      | 118,964| 119,756   | 119,756| 1.47     | 30     | 1.41      | 30     | 1.41     | 0.67      | -4.06 |                 |     |     |          |        |
| 3      | 574,575| 575,213   | 575,213| 0.86     | 86     | 0.81      | 86     | 0.81     | 0.11      | 6.32  |                 |     |     |          |        |
| 4      | 6,457  | 6,438     | 6,438  | 1.1      | 5      | 1.14      | 5      | 1.14     | -0.29     | -3.26 |                 |     |     |          |        |
| 5      | 4,480  | 4,531     | 4,531  | 1.52     | 4      | 1.57      | 4      | 1.57     | 1.14      | -2.65 |                 |     |     |          |        |
| 6      | 2,882,573 | 2,883,375 | 2,881,781 | 1.87 | 2375 | 2.35 | 0.03 | 20.53 |
| 7      | 186,651| 186,738   | 186,738| 2.52     | 18     | 2.69      | 18     | 2.69     | 0.05      | -6.06 |                 |     |     |          |        |
| 8      | 20,513 | 20,494    | 20,494 | 2.65     | 2      | 2.65      | 2      | 2.65     | -0.09     | 0.13  |                 |     |     |          |        |
| 9      | 48,444 | 48,456    | 48,456 | 2.14     | 6      | 2.12      | 6      | 2.12     | 0.02      | 0.78  |                 |     |     |          |        |
| 10     | 25,322 | 25,219    | 25,219 | 0.95     | 21     | 0.95      | 21     | 0.95     | -0.41     | -0.45 |                 |     |     |          |        |
| 11     | 234,288| 234,231   | 234,231| 0.98     | 37     | 0.91      | 37     | 0.91     | -0.02     | 8.31  |                 |     |     |          |        |

| Total   | 4,115,556 | 4,117,857 | 4,116,263 | 1.7 | 2,592 | 2.26 | 0.06 | -24.85 |

Figure 3. Resource quantity estimation result swats plots (X, Z direction)
2.3. Resource estimation

A block model has been established in the range of mining area, which covers the mineralisation range of the whole orebody and is constrained by the mineralized body models. The parent block size of the block model selected in this resource estimation is 50 meters *100 meters *5 meters, and the sub-block size is 12.5 meters *25 meters *1.25 meters. The composite sample string files are obtained by down hole sample combination method, and the string file data are extracted to estimate the grade of the all un - estimated blocks in the block model. The selected estimation method is Ordinary Kriging method. The parameters determined based on the analysis procedure of fitting the variational function model, such as blocks, thresholds and ranges, are inserted into the three-dimensional geological software to complete the estimation of all relevant blocks in the block model. The formula used for calculating the resource tonnage is as below.

\[ Q_m = C_i \times V_i \times \rho \]  \hspace{1cm} (6)

In formula (6), \( Q_m \) is the total metal amount, \( V_i \) is the bulk volumes,\( C_i \) is the the block average grades, \( \rho \) is the ore weights.

The total reported resource numbers by classification are as below Table 3,

Table 3. Resource Summary Table

| Classification | Mineral Resource | Quantity | Au |
|----------------|------------------|----------|----|
|                |                  | Mt       | g/t| Koz |
| Indicated      |                  | 5.38     | 2.24| 386 |
| Inferred       |                  | 2.28     | 1.72| 126 |
| **Total**      |                  | 7.65     | 2.08| 512 |

Surpac 3D geological modelling and estimation software was used for resource estimation, the total gold tonnage estimated and reported as 7.65 million tons and the gold metal including Indicated and Inferred classification resource are 512 koz at the lowest industry grade of 1 g/t. Meanwhiles, according to the final reporting results of the resource numbers, the tonnage and grade curves are created for the better understanding of the relationship between the reporting cutoff grade and tonnage, average grades (Figure 4).

![Figure 4. Tonnage and grades curves](image)

As can be seen from Fig. 4, there is an inverse relationship between gold ore and grade. According to the latest market prices, production numbers and operation costs, we can adjust the current indicators in real time, such as ore grades and selected grades. Under the variable product market prices, the lowest mining industrial reporting grade may be adjusted according to the tonnage grade curves to ensure the rationality and orderliness of mining activities.

Compared with traditional resource estimation methods like IDW method and actual historical mining data, the resource process of geological statistical estimation is more representative and correct, which can reveal the actual situation of the research object, and can also guide the further exploration and mining in the mineralized areas more effectively.
3. Conclusion
Based on the theory of geostatistics and application of Surpac software, a three-dimensional geological model of gold deposit is constructed. Meanwhile, the experimental semi-Variation function of the selected main mineralized body’ strike, dip and vertical directions were used as main research object. The theoretical variation function cures are used as reference and fitting works are completed and related variation parameter are extracted accordingly. Based on the final resource reporting results, the total gold mineral tonnage is 7.6 million tons, 512 Koz gold metal with 2.08g/t grade at industry cutoff grade of 1 g/t. Compared with the traditional IDW method, the 3D geological software based on Kriging estimation method is more reasonable for the irregular samples distribution analysis and closer to real situation. Also, the classification comparison table and block model swats plots are applied to verify the block model, which provided more proofs for the rationality of the estimation method and results. In addition, the mine grade-tonnage curve is analyzed, which provides additional theoretical guidance for selecting different industrial grades in mining and production in the future based on fluctuated metal prices.

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