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A novel algorithm for designing the layout of additional boreholes

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ABSTRACT

In an exploration project, the placement of additional boreholes is based on the available information and engineering judgment, which may result in a lack of information or redundant information in decision making. This paper presents the use of dynamic multistage sampling to design directional and vertical boreholes to scan the subsurface. For this purpose, the potential collars of boreholes are determined within the survey area, while the imaginary boreholes in the form of cone sides cover the area's lateral surface area, and the concentric cones around the collars change with azimuth and dip angles. The objective function is a criterion used to determine the optimal borehole(s) and update the input borehole database in each stage; this iterative process continues until a stopping condition is satisfied. The presented algorithm was executed and validated on both synthetic and field data from the Eastern Kahang region in Iran. In the synthetic case, five additional boreholes were designated based on high grade and estimation error objectives that intersect two parts of the ore body. Ten proposed additional boreholes in the northeast region of Kahang coincided with the high grade copper mineralization zone.

1. Introduction

Sampling is the most widely used method to provide reliable and precise representation information from a large population, which plays a crucial role in site assessment (Myers, 1997). The spatial variability is one principal criterion in designing the optimal sampling scheme. Implementing multistage sampling can improve data efficiency, reduce costs and more accurately model the spatial variability through the site (Marchant and Lark, 2006). In complementary sampling stages, it is challenging to accomplish the following two tasks: determine how many samples are required to approach the defined objectives during each phase and where to locate the additional samples in a sequential manner through the primary sampling network (Haldar, 2013; Myers, 1997). To perform these tasks, an objective of the additional boreholes must be defined in terms of uncertainty, and optimality criteria must be used to assess the value of a new borehole (Rossi and Deutsch, 2014). Boreholes are frequently used to investigate the subsurface and obtain information in the third dimension; the core samples from boreholes are used to estimate the properties of the entire reserve (Boulding, 1993; Evenick, 2008; Knödel et al., 2007).

To optimize the sampling design of boreholes, three concepts have been applied: probabilistic geometry, geostatistical error management, and information theory (value). In the first approach, the optimum hole spacing is computed considering the intersection probability of the drilling network and the target, which is varied as a function of the geometry of the target, the sampling pattern, and the relative orientation of the target to the grid (Houseknecht, 1982; Schejbal, 1998; Shurygin, 1976; Singer and Wickman, 1969). The optimum grid spacing was evaluated by maximizing the gross drilling return based on the probability of detecting the target, the value of the target, and the cost of drilling (Drew, 1979; Geoffroy and Wignall, 1985). Geostatistical error management is the most popular technique for designing the optimal sampling scheme; this technique can be used in many disciplines (Myers, 1997). This technique attempts to significantly reduce the kriging variance by designing samples in areas with high error values. The samples are either selected one candidate at a time or the sets of locations are based on minimizing the kriging variance, and the number of samples (budget limitation); a geostatistical approach has been developed by utilizing simulation and optimization algorithms on various objective functions (Brus and Heuvelink, 2007; Chou and Schenk, 1983; Delmelle and Goovaerts, 2009; Gershon et al., 1988; Szidarovszky, 1983; Van Groenigen et al., 1999; Walton and Kauffman, 1982).

Hassanipak and Sharafodin (2004) introduced an objective function, including estimated grade, ore thickness, and estimation error, to define the optimum locations of additional exploratory boreholes in mineral exploration fields. In the information theory concept, complementary samples are located in the area with the maximum information, thereby causing highly decreased entropy (Chen et al., 2008; Soltani and Hezarkhani, 2011).

In most studies, the collars of additional boreholes are defined based on the distribution map of the intended objective function, which is generated by assigning the average of objective function in a vertical block column to the 2D coordinates on the map. Although the sections of ore deposit are utilized to design a borehole pattern in more recent

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research studies, these methods cannot optimally model the 3D path of additional boreholes. In the present novel algorithm, we use 3D line geometry to search all of the potential boreholes. The probability space of the boreholes for each candidate collar is a cone, with its apex angle changing with dip. The optimum borehole is defined based on the objective function to update the database of boreholes. This loop iterates until the stopping condition is met.

2. Methodology

We aim to present a multistage sampling algorithm that is capable of dynamically identifying the optimal pattern of boreholes with dimensional and directional parameters. In the proposed algorithm, there are two types of functions: objective function, which selects the optimum boreholes with their directional and dimensional properties, and stopping function, which determines the number of boreholes. Note that the algorithm codes are developed using MATLAB® software. The steps of the algorithm are expressed as follows:

1. Select the collar coordinates as the top point of the boreholes:
    - 1.1 Insert the primary network of the drillings.
    - 1.2 Generate the grid based on the maximum and the minimum of the coordinates and arbitrary spacing values in the X- and Y-directions of S_x and S_y, respectively.
    - 1.3 Define the boundary around the deposit and remove the grid nodes that fall outside the polygon area.
    - 1.4 Calculate the Euclidean distance matrix (EDM_{pg}) between m coordinates of the primary network ($X_{p,\ i}$, $Y_{p,\ i}$) and the n grid nodes ($X_{g,\ j}$, $Y_{g,\ j}$).

$$EDM_{pg}=\begin{bmatrix}\left\|\left(X_{p,1},X_{p,1}\right),\left(X_{g,1},X_{g,1}\right)\right\| & \cdots & \left\|\left(X_{p,m},X_{p,m}\right),\left(X_{g,1},X_{g,1}\right)\right\| \\ \vdots & & \vdots \\ \left\|\left(X_{p,1},X_{p,1}\right),\left(X_{g,n},X_{g,n}\right)\right\| & \cdots & \left\|\left(X_{p,m},X_{p,m}\right),\left(X_{g,n},X_{g,n}\right)\right\|\end{bmatrix} \tag{1}$$

    - 1.5 Find the minimum distance of each grid node to the primary collars.
        - *Approach a: regular sampling.*
    - 1.6 Remove the grid node, setting its minimum distance to be less than the minimum spacing values of S_x and S_y.
    - 1.7 The remaining nodes are introduced as the potential collars.
        - *Approach a: irregular (scatter) sampling.*
    - 1.8 Detect the maximum between all of the minimum pair distance grid nodes and the primary collars, max(min(EDM_{pg})).
    - 1.9 Find the corresponding grid coordinates to the mentioned distance in the previous step.
    - 1.10 Assign the grid coordinates to the candidate collar with its priority.
    - 1.11 Remove the coordinate from grid nodes and add it to the primary network coordinates.
    - 1.12 Go to (1.1), until max(min(EDM_{pg})) is greater than or equal to the minimum acceptable borehole spacing. Fig. 1 depicts the regular and irregular approaches to design the pattern of the potential collars.
2. Estimate the 3D spatial distribution of grade:
    - 2.1 Model variograms and anisotropy using the primary input data.
    - 2.2 Estimate the grade using block kriging (G_c) and kriging variance (V_c) at the center of each block (X_c, Y_c, Z_c).
3. Generate and scan the 3D coordinates of the imaginary potential boreholes:
    - 3.1 Insert the collar as the top point of the imaginary borehole (vertical borehole: azimuth = 0° and dip = −90°).
    - 3.2 Calculate the coordinates of the next point based on the collar coordinates, the distance from the collar, the azimuth, and the dip of borehole (Fig. 2a).

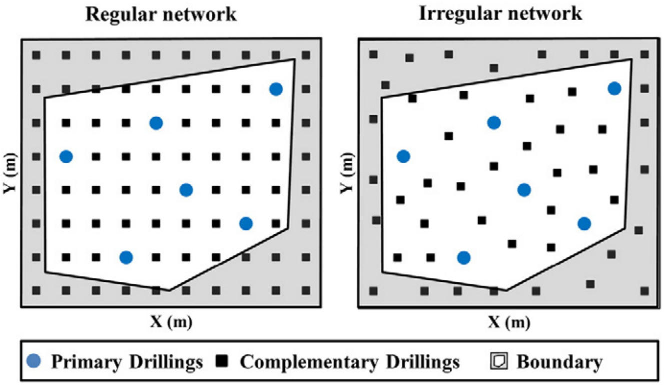

Fig. 1. Schematic pattern of the potential collars based on the primary collars of drillings.

    - 3.3 Repeat (3.2) until all points of the borehole are obtained, taking into account the boundaries of the X-, Y-, and Z-directions.
    - 3.4 Update the azimuth and dip angles of the borehole considering the azimuth and dip tolerances (α, β), the minimum acceptable dip, and the maximum acceptable length, and then go back to (3.2). Fig. 2b and c each shows an imaginary cone that includes the potential boreholes.
    - 3.5 Select the next collar coordinates.
    - 3.6 Go to (3.2) and repeat the subsequent steps until all collars are examined (Fig. 2d).
4. Objective function:
    - 4.1 Assign the grade (G_c) and kriging variance (V_c) to each point of the imaginary boreholes based on the minimum distance to the coordinates of the block center.
    - 4.2 Calculate an objective function considering the grade, error, thickness, etc. at each point.
    - 4.3 Accumulate the values of the objective function along each borehole.
    - 4.4 Find the optimal borehole and its directional and dimensional properties, considering the maximum accumulative value of the objective function.
    - 4.5 Add the optimal borehole to the primary network of drilling and remove its collar from the candidate collars.
5. Stopping criteria:
    - 5.1 Compute the changes in the average kriging variance (KV) per extra borehole.
    - 5.2 Apply the cross validation: The cross validation procedure employs composited grade to compare the actual grades of original boreholes with their estimates (before additional boreholes). In fact, cross validation evaluates the improvement in estimation accuracy to stop the algorithm.
    - 5.3 Evaluate the average algorithm performance using such methods as the kriging variance (KV), the root mean square error (RMSE), and the mean absolute percentage error (MAPE).

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{i=1}^{n}\left(Z_i-Z_i^{*}\right)^{2}}{}n}, \tag{2.1}$$

$$\mathrm{MAPE}=\frac{1}{n}\sum_{i=1}^{n}\frac{\left|Z_i-Z_i^{*}\right|}{Z_i}*100, \tag{2.2}$$

where Z and Z^* are the actual and estimate values of n samples, respectively.

    - 5.4 Go to (1.1) and repeat the subsequent steps until the stopping conditions are satisfied.