Numerical estimation of fracture network permeability based on GEOFRAC model for groundwater modeling in a tin mine

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ABSTRACT

Numerous geological research studies and mining operations have proved that fracture is one of the important factors controlling groundwater flow, mineralization, and ore distribution in metallic deposits. Most current approaches to groundwater flow simulation of naturally fractured media rely on the calculation of equivalent permeability tensors from a discrete fracture network (DFN). This study is aimed at developing a rational two-dimensional DFN by GEOFRAC, a geostatistical method of fracture direction and locations of sample data from a tin mine in the Gaosong area, Gejiu city, southwest China, and utilizing 3,724 outcrop fractures sampled on the ground of mountain Gaosong. Principal inputs of the DFN are density, direction, and continuity of disks that constitute a fracture plane. Fractures simulated by GEOFRAC were validated in that their directions corresponded well with those of the sample fractures. The permeability tensor of each modeling grid was then calculated based on the fracture network constructed. The results showed that GEOFRAC is valuable for two-dimensional DFN modeling in mines and other fracture-controlled geological phenomena, such as groundwater flow and slope failure.

Key words | discrete fracture network, fault distribution, geostatistics, groundwater flow, permeability tensor

INTRODUCTION

Groundwater is water stored in the voids below the aerated zone. The source, composition, and burial conditions of groundwater are complex, so the groundwater flow becomes very sophisticated. Due to the strong human engineering activities in mining areas, underground rock structure has become more complicated, which makes groundwater flow in mining areas more complicated (Caine et al. 1996). This greatly affects the implementation of drainage in mining activities and the efficient and rational exploitation of groundwater use. Clarifying the spatial distribution of fractures in a mining area plays a very important role in utilizing groundwater resources, and supporting economics and urban development in the mining area (Qiao et al. 2017). Building a model between fracture network and groundwater flow can also rationally arrange drainage projects in mines to prevent water inrush accidents and reduce mine accidents. Moreover, considering the background of China’s vigorous promotion of deep mining in the earth, it is more urgent to carry out simulation studies of groundwater flow in mining areas.

Research into groundwater flow simulation on fracture scale can be divided into laboratory measurements and field surveys. The research objects can be divided into single fractures and fracture networks. The research mainly focuses on properties of a single fracture (such as trace length, aperture, roughness, etc.), hydrological characteristics of overall properties of the fracture network (such as density, stress, hydraulic conductivity, connectivity,
permeability, etc.), and summary and verification of local cubic law and the Reynolds equation in experiments (Garven 1995; Boutt et al. 2010; McIntosh et al. 2010). The spatial distribution of the fracture network in these studies is mostly a stochastic model. The spatial distribution of the fractures is randomly generated according to the statistical mean and variance of the sample fractures. It is very different from the spatial distribution of the actual fracture network in rock mass. Moreover, the analysis of single and a few main control water fractures cannot well reflect permeability in a fracture network, and it is difficult to grasp the groundwater flow in a whole region or mining area from a global perspective. Most unsteady flow studies focus on homogeneous loose layers (such as Quaternary accumulations), and there is a lack of research on the variation of groundwater flow in heterogeneous bedrock in time.

In the actual rock mass, the hydrological characteristics of the fracture network system (including faults, seams, joints, fissures, and veins) and its spatial distribution are the major influencing factors in groundwater flow path, generating and forming polymetallic ore bodies with variable shapes. The permeability tensor of the fracture network is the main reason for the large-scale rapid flow of groundwater, and it is also the key to mastering groundwater flow path and water collection. The Gejiu tin mine is located in the southeastern part of Yunnan province, southwest China.

This modeling is equivalent to the development of a discrete fracture network (DFN) model. A DFN constitutes groups of fractures with different properties like locations, orientations, and widths. Many researchers have analyzed DFNs (Acuna & Yortsos 1995; Liu et al. 2016); however, the methods in this research stochastically allocated attributes for simulated fractures usually utilizing Poisson or Gaussian functions accessed from survey data. Spatial features of locations and directions of natural fractures cannot be reflected by such DFN results.

In order to solve this issue, a geostatistical simulation method for fracture (Koike et al. 2012, 2015) is capable of application to model a rational DFN using actual sample fracture data attributes like locations and directions. By connecting closely and likewise oriented disks, the proposed method has the benefit of fracture plane simulation with random shape and size. This study is aimed at further utilizing the ability of GEOFRAC by selecting an investigated area in the Gejiu tin mine and modeling a proper DFN that contributes to interpretation of the surface water and groundwater flow mechanism, prevention of water inrush accidents in mines, and safe mining planning and management.

STUDY AREA AND DATA ACQUISITION

Geographically, the mining area is located in the southern part of the middle-Dian Plateau, an alpine hilly area. The mountains in the area are continuous, heavy and overlapping, and there is no obvious trend; they are mostly blocky mountains. The mountainous area accounts for 86% of the total area of the region. The terrain is generally higher in the east, west, and central regions, and lower in the south and north. The northeast consists of mountain fault depression and lake basin alluvial area, with an altitude of 1,100–1,400 m (m.a.s.l.). The southwest is cut by the Red River and its tributaries. The terrain is broken, the valley is steep, the relative height is 500–1,500 m, and the lowest point is 150 m. The central part of Mountain Lianhua and Mountain Monkey is the watershed of the Honghe River System and the Nanpan River Water System. It is above 2,000 m.a.s.l, and the highest point of this area is 2,766 m.a.s.l.

According to the characteristics of water properties and types of water media in various layers, the groundwater in the area is divided into carbonate rock fissure cave water, clastic rock fissure water, igneous rock fissure water, and Quaternary loose deposit pore water. The southern boundary of the region is basically controlled by the surface water system of the Red River, the western boundary is controlled by clastic rocks and igneous rocks, the eastern and northern parts are controlled by the Triassic clastic rocks, and Permian Gejiu carbonate rocks.

The groundwater of the above three hydrogeological units is almost always supplemented by atmospheric rainfall, and the local ploughed area receives irrigation water for infiltration. Its recharge is related to rainfall, topography, structure, lithology, and karst development conditions. The high mountain area has large rainfall, dense forests, and a large amount of groundwater recharge; and the groundwater recharge is also large in the gentle terrain, rock fissures, and
karst development areas. The hillside and the moderate zone constitute the main recharge area, and the recharge area is wide. Among them, the depression, the funnel, and the falling water cave form a groundwater recharge channel, and the groundwater is vertically recharged by atmospheric rainfall. The slope from the ridge to the valley is often a runoff area. The groundwater moves along the inclined karst fissures and pipelines, and the runoff is rapid. The local stream naturally constitutes the groundwater discharge standard.

The Gaosong mine is situated in the northern part of the tin mine in Gejiu (Figure 1), which is restricted by the Gejiu and Jiajieshan Faults in a north–south direction and the Gesong and Beiyinshan Faults in an east–west direction, and is covered mainly by dolomite and dolomitic limestone of the middle Triassic with dispersed distribution of Tertiary mudstone and Quaternary residual deposits. The study area was a rectangular area of 17 km by 9 km that covered the Gaosong mining area (Figure 1).

An investigation of outcrop faults and fractures was conducted on the ground of Mountain Gaosong. The whole study area was divided into fine grids of size \(100 \text{ m} \times 100 \text{ m}\). Within each grid, different outcrop fractures of trace length, orientation, density, and aperture in one sample point were surveyed. There are 3,724 samples of outcrop fractures, and Figure 2 shows the sampling points in this study. The size of the grids in GEOFRAC modeling and permeability tensor calculation is also \(100 \text{ m} \times 100 \text{ m}\) for the sampling size.

**GEOFRAC METHOD**

Fracture distribution is a complicated simulation problem because of the peculiar characters of fractures. Fracture networks often possess hierarchical features and scaling invariance. To construct the characteristics, GEOFRAC, which consists of a geostatistical technique and principal component analysis (PCA), is proposed to simulate fracture distribution by estimating location, simulating direction, and connecting fracture elements.

Fracture locations are depicted by their center points in the space. Although fracture locations are always biased and show clusters in the space, fracture density (FD) normally...
presents normal distribution. Accordingly, FD can be an appropriate tool for estimation of the fracture location distribution. FD is defined as fracture number per unit length, alternatively fracture length per unit area or fracture area per volume. A variogram is utilized to clarify spatial correlation from FD. Then, ordinary kriging (OK) or sequential Gaussian simulation (SGS) is used to model the FD distribution using the variogram model. The SGS method presents better results according to Koike et al. (2001) because SGS can reduce the smoothing effect. After the estimation, a FD value, which means the fracture number in the cell, is assigned to all the cells. Then, fracture spatial locations are generated by the Monte Carlo method following a uniform distribution from the simulated FD.

Fractures generally have dominant directions due to the tectonic stress field, which implies that the direction data cannot be used directly in OK. Therefore, PCA is employed. For the fracture direction range, groups falling into the direction angle are assigned as 1 to represent fracture appearance, while other groups are assigned as 0 in n groups. For example, strike $\pi/4$ is grouped into NE for the related indicator as (0 1 0 0). When the range is 3D space under the consideration of strike and dip, $n = 8$ is acceptable. Because the indicator set of fracture orientation includes many components, PCA is applied to reduce the group dimensions. The variogram of each principal component is calculated to detect potential correlation in space. Distributions of all the principal components (usually 3 or 7) are modeled by OK or SGS in each modeling grid.

Those components’ values estimated at each location are inversed to the original indicator form, and only the largest value is replaced by 1 to represent the most possible group where the fracture occurs, and the rest are assigned 0 for absence.

Connecting simulated fractures are examined under criteria on the direction and position. Fractures are considered as a spatial plane and the criteria include distance and angle between two fracture planes. $L_s \leq PL$; $L_s$ is the distance between two fractures, and PL is the permitted length. $\varphi \leq PA$; $\varphi$ is the angle between two fracture planes, and PA is the permitted angle.

The connected fractures are connected as one fracture plane using their locations. A real fracture plane itself is in a complicated shape which shows different directions at different positions; thus, they must be connected by triangulation similar to those in a two-dimensional (2D) space. Another method for the connection of several fractures is making a plane using their average strike and dip: this plane is bounded by the projections of edge fracture locations. If a fracture is not connectable to other fractures, it is shown as a spatial circle with a defined diameter according to its strike and dip.

Furthermore, apertures of fractures are estimated by OK or SGS. Fractures in the same direction group are estimated when it is difficult to calculate the variogram in all directions.

2D fracture network model

The preliminary result of outcrop samples shows that aperture of fracture in the study area falls in the range of 0.05–0.2 mm and is concentrated between 0.1 and 0.15 mm. A few samples’ apertures are greater than 0.2 mm. FD distribution is concentrated in the range of 3–8 strips/m while fracture trace length distribution ranges from 0.5 to 2 m. Histogram of the aperture, FD, and trace length show normal distribution, which proves the surveyed data are suitable for geostatistical modeling (Figure 3). A unit grid size of FD will be decided by the sample data in the first step. The histogram of FD will be approximated as a normal distribution for the subsequent modeling steps. The result of DFN resolved by GEOFRAC can be verified as follows: correspondence of directions between the simulated and sample fractures, positional agreement of the simulated fractures with the known faults. Figure 4 shows the fractures...
simulated by GEOFRAC, and Figure 5 shows continuous fractures with length roughly longer than 300 m. The simulated fractures show good consistency with the geological map.

**CALCULATING PERMEABILITY**

Fault composition and associated permeability structures establish control on fluid flow in shallow earth crust (Caine et al. 1996; Lu et al. 2016). The two-dimensional distributions of the simulated outcrop fractures can be integrated with the permeability tensor model to estimate permeability of outcrop fractures and rock masses. The permeability tensor, \( k_{ij} \) is expressed by Oda’s equation (Oda et al. 1987):

\[
k_{ij} = \lambda \left( P_{ij} - \delta_{ij} \right)
\]

\[
P_{ij} = \frac{\pi \rho}{4} \int_0^\infty \int_0^\infty \int_0^{\Omega} r^3 n_i n_j E(n, r, t) \, d\Omega \, dr \, dt
\]

where \( \delta_{ij} \) is a delta function, \( \lambda \) is a constant of continuity of fractures, \( r \) is diameter of the fracture, \( t \) is hydraulic aperture of the fracture, \( n \) is a normal vector of the fracture plane, \( E(n, r, t) \) presents the density function, \( \rho \) is FD in volume, and \( \Omega \) is a solid angle. \( P_{ij} \) can be discretized as:

\[
P_{ij} = \frac{1}{V} \sum_{k=1}^{N} r_k^3 |n_{ik} n_{jk}|
\]

where \( V \) is the volume of the study region. \( V \) and \( r \) are alternative to the area and trace length of the fracture in two-dimensional analysis. It was assumed as \( 10^{-6} \) times \( r \) for determination of \( t \) by examining the validity of the
order of the calculated permeability. Figure 6 shows the calculated permeability in the study area. The calculated result shows consistency between permeability and the main fractures and faults in the study area.

CONCLUSION

This study planned to build a rational DFN in a metallic mining area by selecting the Gaosong mine in southwestern China to depict the relationship between fracture distribution and permeability tensor. The GEOFRAC method was validated by consistency of major tendencies in simulated fractures’ directions with those of outcrop sample data and positional agreement of the continuous fractures with the actual faults. GEOFRAC is confirmed as a convincing tool to generate a rational DFN that can describe restrictions of fractures on the groundwater flow path and contribute to prevention of mine water inrush accidents. The calculated permeability shows consistency with the main fractures and faults in the study area.

Future works could reduce bias in sampled fractures’ direction, consider fractures’ widths for modeling more plausible DFN and to generate a more general fracture network with both ground network and underground network. By using such systematic fracture networks with calculated permeability, groundwater flow can be simulated in this tin mining area.

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REFERENCES


