

Artigos

Integration of discrete fracture networks and flow simulator for quantification of hydrogeological uncertainty

Integração de redes de fraturas discretas e simulador de fluxo para quantificação da incerteza hidrogeológica

Caetano Pontes Costanzo¹; Alexandre Campanhe Vidal¹; Bruce Marshall² ✉

¹ Universidade Estadual de Campinas (UNICAMP), Campinas, SP

² University of British Columbia, Canadá

✉ caetano.costanzo@gmail.com, vidal@ige.unicamp.br, brucejmarshall@gmail.com

Keywords:

Discrete fracture networks;
Hydrogeological uncertainty;
Groundwater flow;
Open-pit mines.

Palavras-chave:

Redes de fraturas discretas;
Incerteza hidrogeológica;
Fluxo subterrâneo;
Mina a céu aberto.

Revisão por pares.
Recebido em: 31/03/2021.
Aprovado em: 18/06/2021.

Abstract

In this study, a discrete fracture network model (DFN) and groundwater flow simulation were applied to a fractured aquifer of an open-pit mine. Conditional simulation of the fracture systems was developed to quantify and evaluate the uncertainty of geological structures and to predict possible hydrogeological risks associated with these uncertainties. The method used was based on the statistical characterization and simulation of spatial distribution scenarios of fracture lengths, directions and openings, as well as their influence on water flow behavior. The spatial configuration of the structures was generated using Poisson processes, while the lengths and angles were generated by Gaussian simulation. Flow simulation was performed with Modflow software. The resulting scenarios honored field data and quantified and evaluated the uncertainty associated with fracture distribution. In addition, the study was able to demonstrate the practical aspects of the proposed simulation method, which can then be applied to increase the planning and operational effectiveness of open-pit mines.

Resumo

O modelo de redes de fraturas discretas (DFN) em conjunto com a simulação de fluxo subterrâneo foi aplicado nesta pesquisa em um aquífero fraturado de uma mina a céu aberto. A simulação condicional dos sistemas de fraturas foi desenvolvida e utilizada para a quantificação e avaliação da incerteza das estruturas geológicas e para a previsão das possíveis vazões de escoamento das águas para o fundo de cava. O método utilizado foi baseado na caracterização estatística e na simulação de cenários de distribuição espacial dos tamanhos, direções e aberturas das fraturas e suas influências no comportamento do fluxo. A configuração espacial das estruturas foi gerada por processos de Poisson, enquanto que os tamanhos e ângulos foram gerados pela simulação gaussiana. A simulação do fluxo foi realizada com o software Modflow. Os cenários resultantes honraram os dados e informações de campo e quantificaram e avaliaram a incerteza atrelada à distribuição das fraturas. Por fim, a pesquisa conseguiu demonstrar os aspectos práticos do método de simulação proposto com base nos resultados das vazões de escoamento das águas para o fundo da cava.

DOI: <http://dx.doi.org/10.14295/ras.v35i2.30024>

1. INTRODUCTION

One of the main tasks in hydrogeology is the understanding of underground flow in fractured aquifers (BORGNE *et al.*, 2006). The prediction of geological structures in open pit mines is one of the first issues faced in mining planning. Fractures not only impact the development of mineral exploration, but can also hamper slope stability through the formation of preferred groundwater paths.

In addition, these underground flow in fractured aquifers can significantly increase the volume of dewatering to the mine pit, causing a possible increase in costs for drainage deployment (SUN *et al.*, 2009).

Furthermore, uncertainties about geological structures in the planning phase and during mining operations can lead to sig-

nificant financial losses for the project, due to delays in the exploration schedule, decrease in production and possible losses of reserves. (DIMITRAKOPOULOS; LI, 2000).

Therefore, better evaluation and quantification of uncertainties related to fractures can significantly improve geological and hydrogeological modeling, which is essential for the sound planning and operation of a mine (DIMITRAKOPOULOS; LI, 2000).

In many mining areas, however, there is little available data from initial drill cores and limited access to pit outcrops and embankments to estimate the occurrence probability of fractures.

Geostatistical tools are typically used to generate simulations that can reproduce the spatial variability and uncertainty of dif

ferent parameters, including ore body thickness, piezometric level, faults, fractures, lineaments, among others (PARDO *et al.*, 2013).

The objective of data uncertainty analysis is to understand and describe the spatial patterns of variables such as thickness, fault, and fracture. An important parameter that distinguishes geostatistical estimation from other types is the variogram model, which controls the assigned weights of the variables to known data of surrounding areas (SRIVASTAVA, 2013).

However, the prediction of geological structures in open pit mines is extremely difficult, due to the high dimensional variability and complex formation process of the structures. Thus, researching the uncertainties associated with structural geological mapping can be interesting.

The main objective of this study was to simulate fracture occurrence probability scenarios through analysis of discrete fracture networks, evaluating the impact of these scenarios on groundwater flow. In turn, a discrete fracture network model was integrated with underground flow simulation, there by contributing to the prediction of possible water outflow scenarios

during the operation of an open pit mine over a 10-year period.

2. MATERIALS AND METHODS

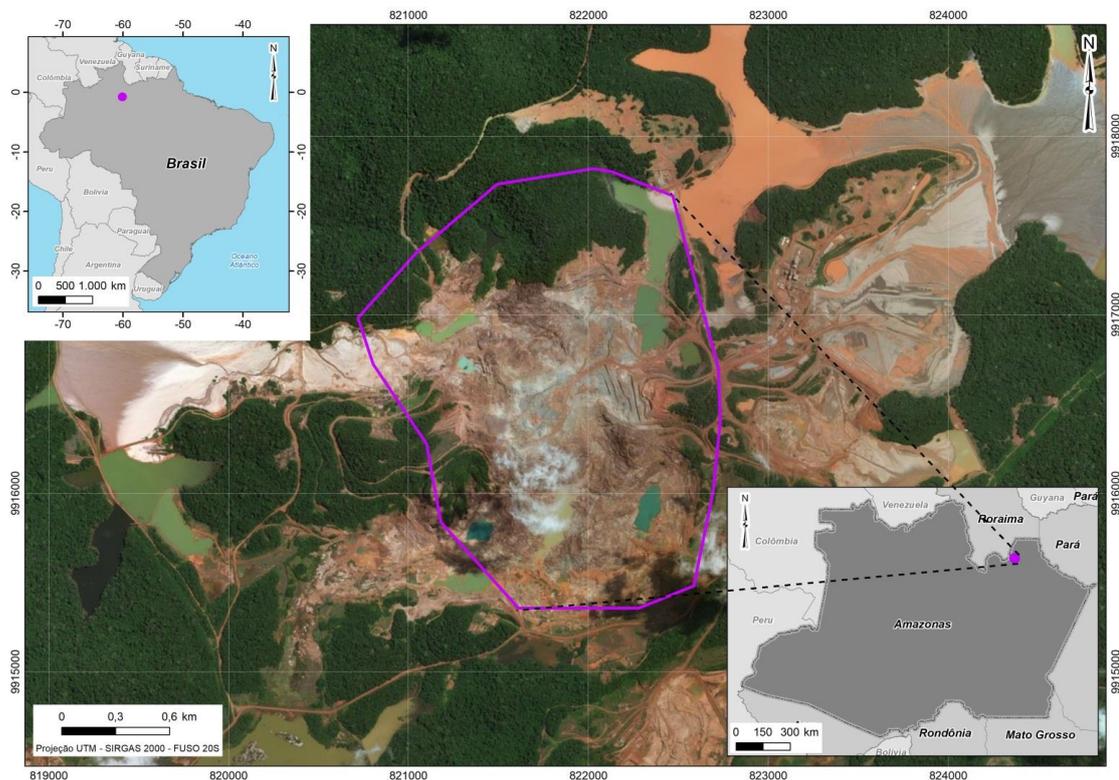
The Mina do Pitinga is located in the city of Presidente Figueiredo / AM, on an east - west branch of the federal highway BR-174, which connects Manaus - AM to Boa Vista - RR.

The northern region of Brazil is characterized by a tropical climate, with the rainy season between November and May and a relatively dry period between June and October (INMET, 2015).

The geology of the area, from the base to the top, is composed of albite granite (220 m - 48 m), amphibole - biotite syenogranite (48 m - 9 m) and soil (9 m - surface).

The mine area covers approximately 946,500 m², with a pit perimeter of 4,342 m. The altimetric quota of the area is close to 200 m. There are two water reservoirs in the northeastern portion of the study area, covering an area of 4.26km² and an estimated volume of 25.6 Hm³ (Figure 1).

Figure 1 - Map of the open-pit area of the mine (circled in purple) and location of water reservoirs to the northeast



2.1. Field research and analysis

The mine database has a total of 337 fracture measurements, consisting of length, direction and openings. This information was compiled by the mining company and has been inserted

into the geo-structural map of the mine, in conjunction with information derived from drilling campaigns and field mapping of accessible slopes of the pit (Figure 2). The mapped fractures present a high density (extremely fractured according to Numer *et al.*, 2003), with large directional variability.

Through analysis of the database, it was also possible to associate the largest lineaments to the fault lines, as well as open fractures with water and those filled by cement and/or dried.

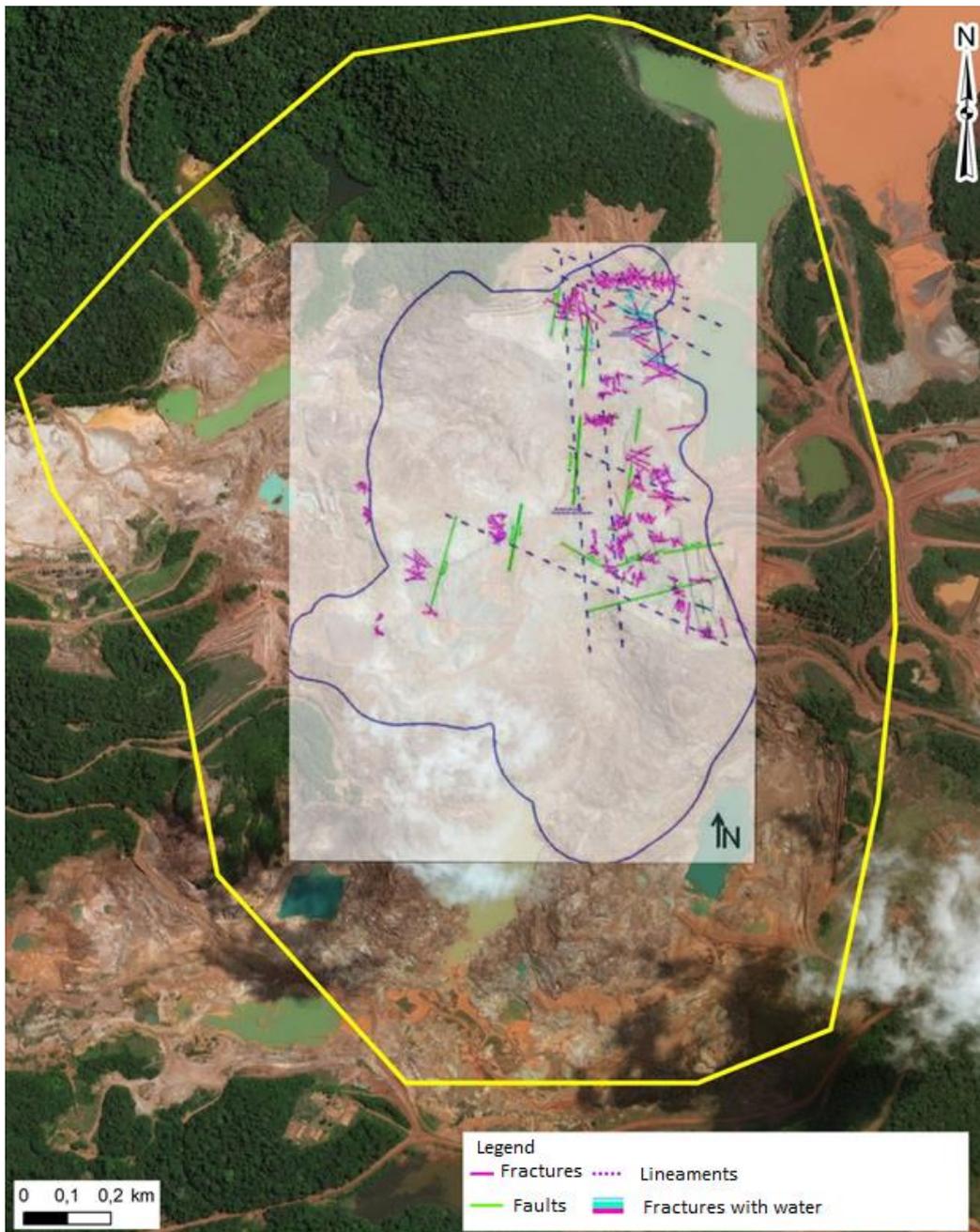
However, as the database does not provide the size of the openings (mm), this information was obtained via bibliographical research. All fractures were considered open, so the opening distance was not considered. Grid cells that are traversed by fracture were considered to have greater hydraulic conductivity.

Openings values were not mapped in the field. Thus, bibliogra-

phic data was used for the values of mean and standard deviation (mm), such as: Long and Billaux (1987), Moreno *et al.*, (1988), Tsang *et al.*, (1988) e Keller *et al.*, (1999).

Therefore, in order to simulate a discrete fracture network models of the entire open-pit mine area, the linearization measures were discarded. The input data used corresponded to (i) fractures; (ii) fractures with water and (iii) faults, which were all grouped together into a single variable called fractures. These fractures were considered vertical.

Figure 2 - Structural interpretation of the study area. Notice that there are large areas of the pit without any geo-structurally mapped information

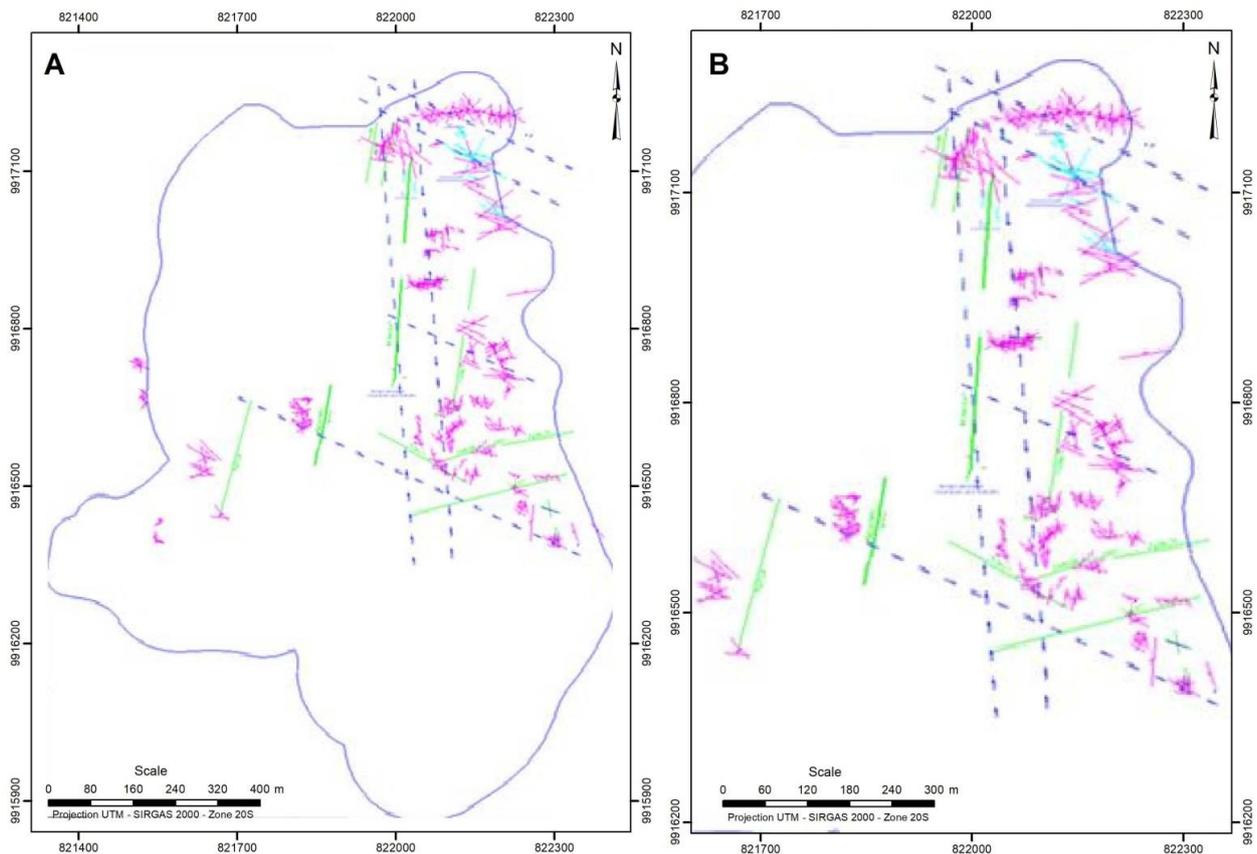


2.2. Discrete fracture network model- DFN

Evaluation of groundwater flow in fractured aquifers can be conducted using numerical or analytical methods that are able to ascertain the field of flow in each fracture. The Discrete Fracture Network (DFN) method is a discontinuous model that is able to quantify fractures within a medium, based on data collected in the field (LONG; BILLAUX, 1987).

It is usual to generate statistical models, as input to the DFN method, which inform values of important geometric properties, valid for the entire fractured aquifer, obtained through measurements carried out in restricted regions, as in this research, which has only the region northeast with a high density of field information (Figure 3).

Figure 3—Large areas of the mine without structural mapping information



The DFN computational algorithm explicitly simulates the geometric properties of each individual fracture, such as orientation, length, position, shape and opening, as well as analysis the topological relationships between individual fractures or a set of fractures. The DFN can be generated from structural geological mapping to represent different types of fractures, including joints, faults, veins and flattened plans (LEI *et al.*, 2017), being an integral part of geological modeling software such as PETREL © and RMS ©. In this research, the PETREL © was used.

The distributional occurrence of fractures in non-sampled areas was determined by the Poisson method (Poisson, 1837). After this simulation, the direction and length of the fractures were assigned to each point, generating histograms for the structures. Then, with the distributions and variographic model showing both length and direction, the sequential Gaussian simulation was performed.

The Poisson distribution is a discrete probability distribution, applicable to occurrences of an event at a specified interval. The random variable x is the number of occurrences of the event within a range, indicating time, distance, area, volume or other analogous unit (DIMITRAKOPOULOS; LI, 2000). The occurrence probability of " x " times within a range is represented by the formula:

$$P(x; \mu) = \frac{\mu^x e^{-\mu}}{x!} \quad (1)$$

Where μ corresponds to the average of the event under analysis.

With Poisson's point distribution maps, the second step was the sequential Gaussian simulation (SGS) in order to simulate the dimension and angle of fractures. Stochastic simulations were performed to generate 50 scenarios with different values for the two variables.

The SGS is the application of a sequential simulation procedure for multigaussian random functions, considering the simulation of N random variables $\{Z(x_i), i = 1, N\}$ and conditioned to the set of n data points $\{z(x_\alpha), \alpha = 1, \dots, n\}$ (DEUTSCH, 2002). In this algorithm, a random value is assigned to each cell that has no experimental data, defining a random order for all cells in the mesh. For each cell, the probability density function (fdp) is estimated based on a number of neighboring conditioning data (initial data and simulated data). A random value of this fdp is then allocated by establishing spatial continuity.

SGS and Poisson model advantages include preservation of natural fracture features (e.g. curvature and segmentation) and unbiased characterisation of complex topologies (e.g. intersection, truncation, arrest, spacing, clustering and hierarchy).

The DFN model used in this research only considered the geometric parameters of the fractures.

Table 1 presents the input data of the DFN model used.

Table 1 – DFN model input

Initial model data	
Simulation volume format and dimensions	Cubic shape: edge dimension Prismatic shape: length; width and depth
Number of fracture families	35
Data for each family	
Volumetric density of fractures	Number of fractures per cubic meter of volume ($1/m^3$)
Fracture length	Average (m) e standard deviation (m) All fractures were considered open.
Fracture opening	Bibliographic data was used for the values of mean and standard deviation (mm)
Fracture orientation	Average diving angle ($^\circ$) and average steering angle ($^\circ$)

2.3. Groundwater flow simulations

The hydrogeological modeling for groundwater flow simulation of the 50 fault and fracture distribution scenarios was performed using Modflow software (U.S GEOLOGICAL SURVEY, 2011). Modflow and modelador simulates the hydrogeological interactions (interactions of fractures in this research), where the geological parameters are incorporated, as well as the main hydrological characteristics and boundary conditions. Modflow is a three-dimensional flow model based on finite differences created by the U.S. Geological Survey, which is widely used to predict the behavior of underground flow systems (U.S GEOLOGICAL SURVEY, 2011).

The initial parameters of the model have the following characteristics:

- 24,000 cells per layer: 150 cells in the x axis direction (4 m) and 160 in the y axis (5 m);
- As 3 layers were considered, the model has a total of 72,000 cells;
- The transient regime was adopted;
- Contour conditions were applied in the northeast edge of the study area, which has the highest elevations;
- The bottom of the model is at -100 m and the model considered 3 elevation layers: Top 1: terrain surface; Top 2: to 20 m; and Top 3: to 50 m;
- The simulation considered two periods, two years and ten years, divided into 10 steps each;
- The point of observation was determined from the lowest level of the model, which receives the largest hydraulic gradient;

- Average monthly precipitation in the region (150 mm/month) was used to simulate natural water replenishment of the reservoirs.

The groundwater flow modeling was performed for the 50 discrete fracture network (DFN) models for aquifers constituted by crystalline rock with structural features. Soil and crystalline rock without structural features were considered in the hydrogeological model.

The contour conditions were defined according to the topography, that is, at the edges of the area which are higher.

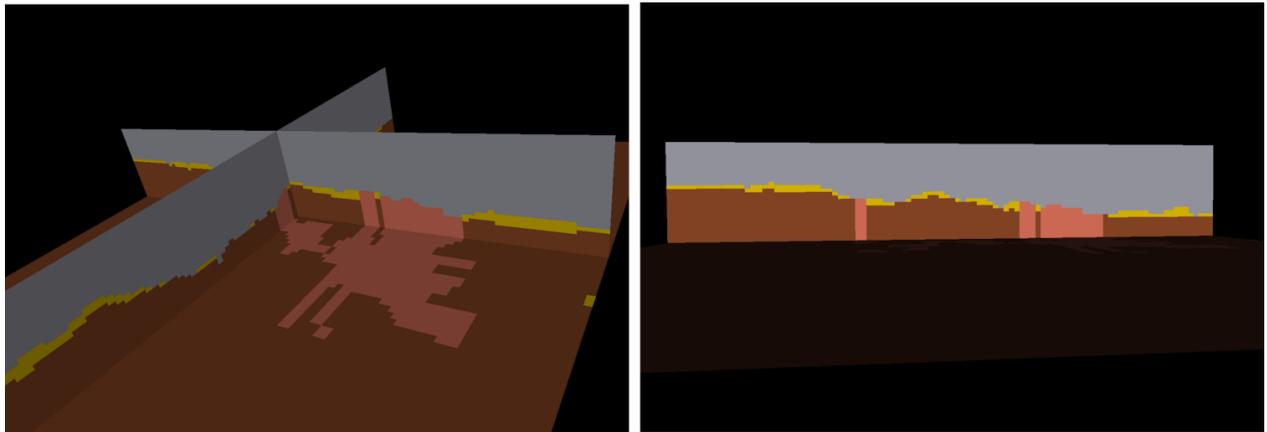
The two water reservoirs in the area were incorporated into the model as a single reservoir with the same characteristics, as they are both situated in close proximity at high elevation and served as water recharge sources for the mine during the whole simulation period. The conduct adopted for the reservoir base was 10^{-2} m/d. This value was obtained from field data by slug test in a drilling beside the reservoirs.

This test consists of inserting a cylinder inside de hole and checking the displacement of water in order to define the local hydraulic conductivity by Hvorslev (1951).

Figure 4 shows the three flow units considered in the model: the upper soil layer in yellow; the mesh cells by fractures in pink; and the cells related to the crystalline rock without the structural features in brown.

Three flow units were defined based on the same database used for the DFN model, that is, drill core interpretations and mine pit slope mapping.

Figure 4 - Model used in groundwater flow simulation. Soil: yellow; Fracture: pink and without fracture: brown.



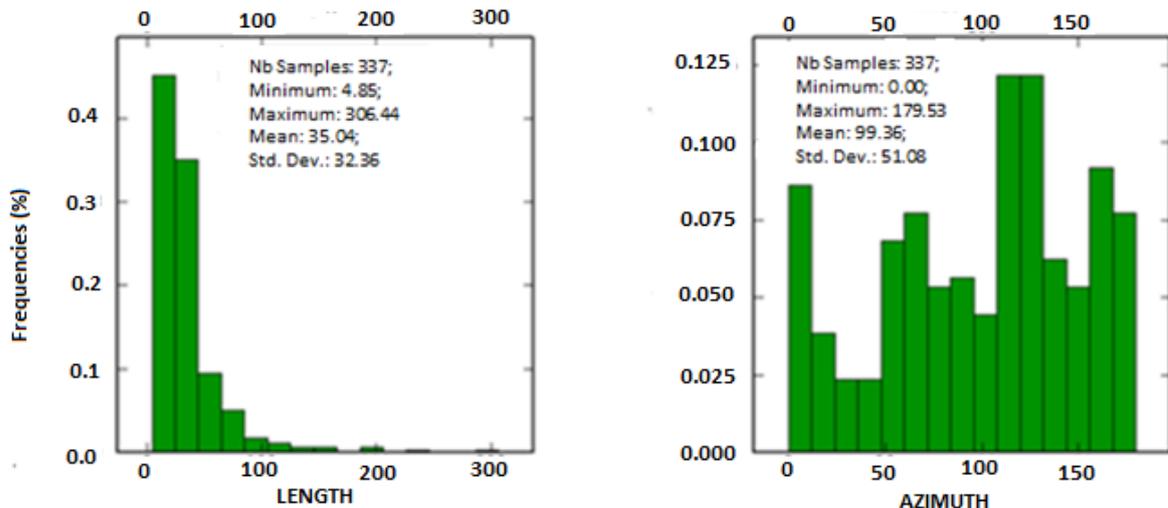
River flow data around the study area and mine spillways were not considered in the hydrogeological model, since the main object of this research was to evaluate the related uncertainty of the structural mapping with the hydrogeological behavior only in the fractured rock.

3. RESULTS AND DISCUSSION

The control data used in the synthetic modelling of the geo-

structural configuration of the open-pit included the directional distribution and length of the fractures, which were derived by variographic means. The directions of the fractures were highly variable, with many aligned in a N99 direction, although there were others with directions of N0, N70, N120 and N160 (Figure 5). The dimensions of these structures varied from 4 to 300 m, with an average size of 35 m.

Figure 5 - Histograms of the lengths and directions of fractures in the open-pit area



Three parameters were chosen for the calibration of the flow model: horizontal hydraulic conductivity, rainfall recharge and reservoir bottom conductivity, the adjusted values were $3.44 \cdot 10^{-7}$ m / s, $1.18 \cdot 10^{-3}$ m / s and 10^{-6} m / s respectively. Hydraulic conductivity and reservoir bottom conductivity were calculated by slug test (Hvorslev, 1951), while rainfall recharge by Siderama station located in Uruará / AM.

A total of 50 discrete fracture network models (DFN) were developed to estimate the length, direction and openings of fractures in the open-pit area of the mine. These models were then used in the hydrogeological modeling (MODFLOW) to estimate underground flow, as well as the subsequent water accumula-

tion in the bottom of the pit.

The geometric results (50 models – DFN) of the models corroborated well with the geo-structural mine data, which has enabled better understanding of underground rock bodies and their associated hydrogeological behavior. DFN and MODFLOW integration makes possible to quantify uncertainties related to how the spatial organization of fractures can influence underground flow behavior.

Table 2 groups these results and shows the calculation of the volume of bottom water (m³) for each DFN group, as well as the flow rate in m³ / h considering 10 years of mining.

Table 2 - Grouping the same results, calculating the volume of water from the bottom of the pit (m³) resulting from the flow of water to the pit of the mine and runoff flow in 10 years of mining

Group	DFN	Water Level (m)	Total Volume (m ³)	Flow Rate (m ³ /h)
01	DFN-4; DFN-6; DFN-10; DFN-34 e DFN-50	1,19	1.126.335,00	12,86 m ³ /h
02	DFN-11; DFN-12; DFN-13; DFN-14; DFN-15; DFN-16; DFN-17; DFN-18; DFN-20; DFN-22; DFN-24; DFN-25; DFN-26; DFN-28; DFN-30; DFN-31; DFN-32; DFN-35; DFN-36; DFN-37; DFN-40; DFN-41; DFN-42; DFN-44; DFN-45; DFN-46; DFN-47; DFN-48 e DFN-49	1,18	1.116.870,00	12,75 m ³ /h
03	DFN-7; DFN-21; DFN-27 e DFN-38	1,20	1.135.800,00	12,97 m ³ /h
04	DFN-8 e DFN-43	1,21	1.145.265,00	13,07 m ³ /h
05	DFN-1	0,94	889.710,00	10,16 m ³ /h
06	DFN-2	0,79	747.735,00	8,54 m ³ /h
07	DFN-3	1,24	1.173.660,00	13,40 m ³ /h
08	DFN-5	92,65	87.693.225,00	1.001,06 m ³ /h
09	DFN-9	1,22	1.154.730,00	13,18 m ³ /h
10	DFN-19	-0,07	-66.255,00	excluded
11	DFN-23	2,51	2.375.715,00	27,12 m ³ /h
12	DFN-29	1,23	1.164.195,00	13,29 m ³ /h
13	DFN-33	15,16	14.348.940,00	163,80 m ³ /h
14	DFN-39	93,39	88.393.635,00	1.009,06 m ³ /h

One of the DFN model scenarios is shown in Figure 6, which highlights the estimated spatial distribution and direction of faults in the open-pit mine site and surrounding area. In turn, the DFN model influences the hydrogeological modeling evaluation used to determine the potential water accumulation in the bottom of the pit, which then allows for future dewatering estimation and planning. However, the generated hydrogeological model is relatively simplified, as it only evaluates the distribution, length and opening of fractures, thereby representing the preferred water paths.

Simulations of fracture systems makes it possible to analyze the uncertainty regarding possible hydrogeological risks during mining operations. For this mine site, there is a critical region between the face of the pit and a reservoir located to the north-east, where the mapped fractures presented water circulation. Therefore, this region is more likely to contribute to an input of groundwater to the bottom of the pit.

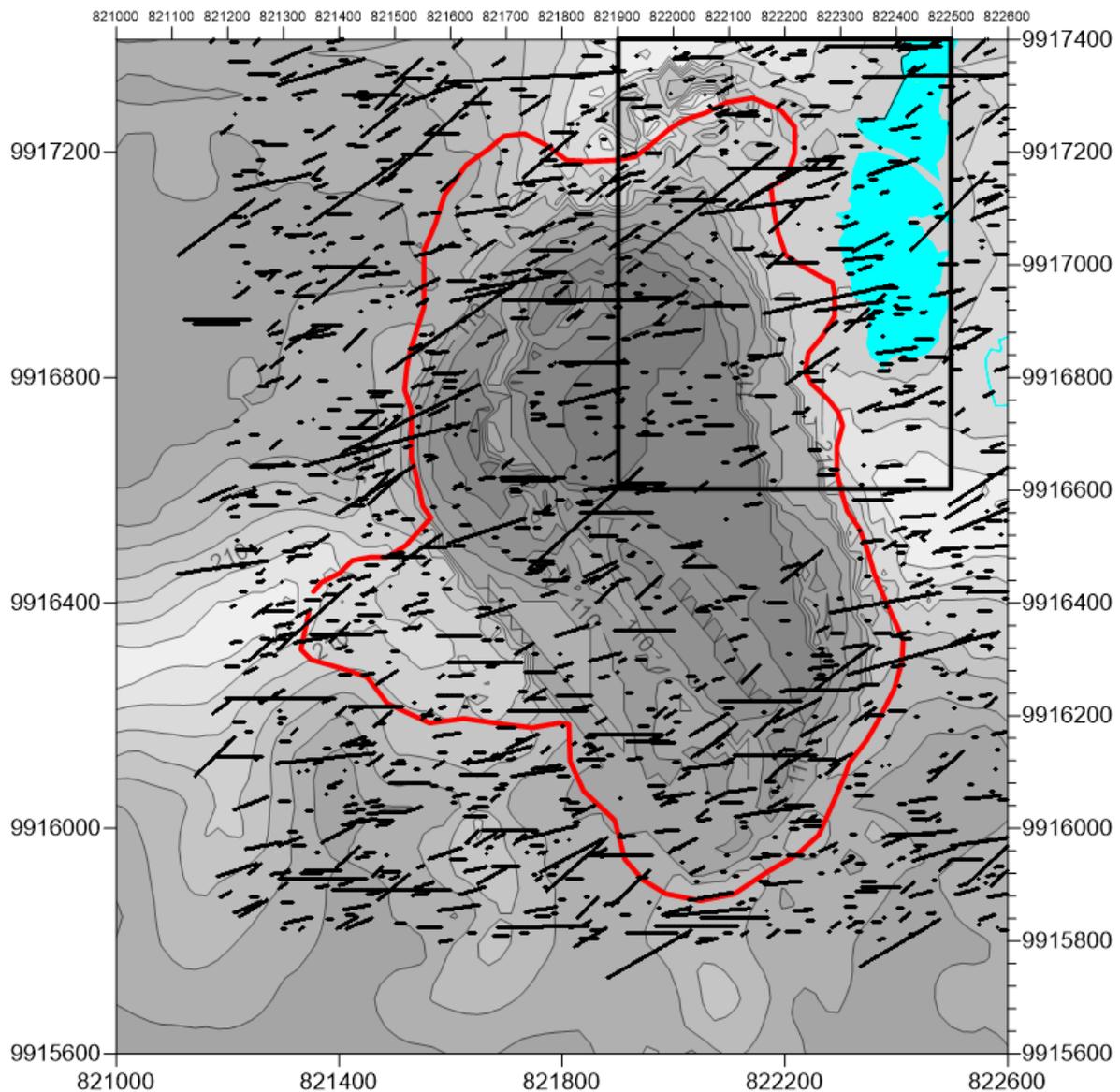
Consequently, the flow simulation was only applied in the northeastern portion of each DFN model in order to evaluate

the influence of fracture distribution on underground flow coming from this direction (Figure 6). The high value of the standard deviation is caused by the presence of anomalous values of flow rate.

The average flow rate and standard deviation for all the scenarios were 56.56 m³/h and 198.87 m³/h, with a minimum of 8.54 m³/h and maximum of 1,009.06 m³/h. The low flow values and resulting water accumulation in the bottom of the pit, including one negative value, may be related to uncertainties in the DFN model. In order to reduce these uncertainties, more geo-structural information from other areas in the pit would be beneficial.

Several models of discrete fracture networks had the same result in relation to the accumulation of water at the bottom of the pit, such as: 5 models had an accumulation of 1.19 m; 29 models had a resulting water level thickness of 1.18 m; 4 simulations with the result of 1.20 m; 2 with 1.21 m; 9 results showed variable water levels and the DFN-19 resulted in a negative water level.

Figure 6 - Results of a DFN model scenario showing the estimated spatial distribution and direction of fractures and the target area of the groundwater flow simulations (NE rectangle).



4. CONCLUSION

The DFN model developed in this study showed that the distribution, length and openings of fractures can be inferred from the original geo-structural map of a mine. The DFN method produced probability simulations that reflected the spatial continuity of the fracture density mapped in the pit area, as well as corroboration with information from the database.

However, integration of the DFN and MODFLOW models generated low flow rate results, due to the lack of field data such as fracture opening thickness, hydraulic conductivity, and transmissivity data.

On the other hand, the research was able to achieve its objective of evaluating uncertainties related to how geological structures influence underground flow behavior. Furthermore, new models can be improved with more field data, which will improve the reliability of results generated by the flow simulator inte-

grated with the DFN interface.

5. ACKNOWLEDGEMENTS

The authors would like to thank Walm Engenharia and Tecnologia Ambiental Ltda. for yielding the data used in the work, as well as the researcher Michelle Chaves Kuroda, who contributed important revisions of the article.

REFERENCES

- DEUTSCH, C. V. *Geoestatistical reservoir modeling*. New York: Oxford University Press, 2002. 376 p.
- HVORSLEV, M.J., Time Lag and Soil Permeability in Ground-Water Observations. *Bull.* n. 36, Waterways Exper. Sta. Corps of Engrs, U.S. Army, Vicksburg, Mississippi, pp. 1-50, 1951.
- INMET - Instituto Nacional de Meteorologia. *Dados meteorológicos: estação meteorológica de observação de superfície*

convencional. Disponível em: <http://www.inmet.gov.br/portal/index.php?r=estacoes/estacoesConvencionais>. Acesso em: jun. 2015.

KELLER, A.A.; ROBERTS, P.V.; BLUNT, M.J. Effect of fracture aperture variations on the dispersion of contaminants. *Water Resour Res*, v. 35, n. 1, p. 55-63, 1999. <https://doi.org/10.1029/1998WR900041>

LE BORGNE, T., O. BOUR, F. L. PAILLET, and J. P. CAUDAL. Assessment of preferential flow path connectivity, and hydraulic properties at single borehole and cross-borehole scales in a fractured aquifer. *J. Hydrol. Amsterdam*, v. 328, n. 1-2, p. 347-359, 2006. <https://doi.org/10.1016/j.jhydrol.2005.12.029>

LEI, Q., LATHAM, J.-P., TSANG, C.-F. The use of discrete fracture networks for modelling coupled geomechanical and hydrological behaviour of fractured rocks. *Comput. Geotech*, v. 85, p. 151 - 176, 2017. <https://doi.org/10.1016/j.compgeo.2016.12.024>

LONG, J. C. S. and BILLAUX, D. M. From field data to fracture network modeling: An example incorporating spatial structure. *Water Resources Research*, v. 23, n. 7, p. 1201-1216, 1987. <https://doi.org/10.1029/WR023i007p01201>

MORENO L., TSANG, Y. W., TSANG, C.-F., HALE, F. V. and Neretnieks, I., Flow and tracer transport in a single fracture: A stochastic model and its relation to some field observations. *Water Resources Research*, v. 24, n. 12, p. 2033-2048, 1988. <https://doi.org/10.1029/WR024i012p02033>

NUMMER, A. R., MIRANDA, A. W. A., CASTRO, A. M. D. R. M. de, & FILHO, D. T. Análise estrutural de fraturas e falhas aplicada

ao mapeamento hidrogeológico em áreas do cristalino: estudo preliminar no município de Seropédica, Rio de Janeiro. *Águas Subterrâneas*, 2003. Disponível em: <https://aguassubterraneas.abas.org/asubterraneas/article/view/23969>.

PARDO-IGUZZI, EULOGIO; DOWD, PETER ALAN; BAL-TUILLE, J. M.; CHICA-OLMO, M. Geostatistical modelling of a coal seam for resource risk assessment. *International Journal of Coal Geology*, v. 112, p. 134-140, 2013. <https://doi.org/10.1016/j.coal.2012.11.004>

POISSON. *Recherches sur la probabilité des jugements en matière criminelle et matière civile*. Paris, Bachelier, 1837.

R. DIMITRAKOPOULOS and LI, S. Conditional simulation of faults and uncertainty assessment in longwall coal mining. In: INTERNATIONAL GEOSTATISTICS CONGRESS PROCEEDINGS, 6., 2000. [Proceedings...]. Cape Town, South Africa, 10-14, April, 2000. P. 1-12.

SUN H Q, BAO SI-YUAN, LI LIN, LIAO TAI-PING. Predicting coal mining faults using combined rock relationships. *Mining Science and Technology*, v. 7, n. 3-4, p. 0745-0749, 2009.

TSANG, Y. W., TSANG, C.-F., Neretnieks, I. and Moreno, L., Flow and tracer transport in fractured media: a variable aperture channel model and its properties. *Water Resources Research*, v. 24, n. 12, p. 2049-2060, 1988. <https://doi.org/10.1029/WR024i012p02049>

U.S. GEOLOGICAL SURVEY, Office of Groundwater. *Status os MODFLOW Versions and MODFLOW-Related Programs Available on USGS Web Pages*, 2011. Disponível em: <http://water.usgs.gov/nrp/gwsoftware/modflow-status-2011Jan.pdf>.