The Application of Discrete Fracture Network Models to Mine Groundwater Studies

Gareth Digges La Touche[1], Mark Cottrell[2]

[1]*Golder Associates (UK) Ltd, Attenborough House, Browns Lane Business Park, Stanton on the Wolds, Nottinghamshire, NG12 5BL, United Kingdom, gdltouche@golder.com*
[2]*Golder Associates (UK) Ltd, Attenborough House, Browns Lane Business Park, Stanton on the Wolds, Nottinghamshire, NG12 5BL, United Kingdom, mcottrell@golder.com*

Abstract Discrete Fracture Network (DFN) modelling represents an alternative approach to the more usual continuum Representative Elementary Volume (REV) methods for modelling groundwater flow in fractured rocks. The basis of DFN modelling is the cognisance that at every scale, groundwater flow in fractured rocks is dominated by a limited number of discrete pathways formed by fracture connectivity. In this paper we present examples of the use of DFN models to mine groundwater studies. Specifically we will consider the use DFN models for the estimation and prediction of groundwater inflow to underground workings and for the evaluation of heterogeneity.

Key words modelling, DFN, FracMan, discrete fracture network, groundwater

Introduction

Many mine groundwater studies involve the construction of models of groundwater flow, and contaminant transport, to test our conceptual understanding of the hydrogeological regime of a mine site. These range from simple analytical models in a spreadsheet, through analytical element models to numerical finite difference and finite element models. As many of the groundwater systems in which mining occurs are dominated by fracture flow reliance is placed on the concept of the representative elementary volume (REV). The REV is taken as that volume of rock at which flow can be simulated as if it were an equivalent porous media and the influence of individual fracture pathways no longer dominates. The discrete fracture network (DFN) approach provides a paradigm for describing rock fractures (and other discrete features such as faults, breccia layers, and dikes) in a systematic and statistically reproducible manner. Fractures, and faults, are represented as discrete surfaces in three-dimensions. The geometrical properties of intensity, orientation, shape and size for the fractures are described deterministically for known features, and stochastically using observed data from borehole core logging, surface mapping, geophysics and remote sensing (e.g. lineaments) correlated to fracture location and geometry. On top of the geometrical description, the transient hydraulic properties of the fractures/faults are derived using calibration to and simulation of in situ measurements and tests.

Groundwater inflow is an important issue for mining, as aside from the potential for flooding, a knowledge of the inflow rates is important for mitigating groundwater and surface water impacts in terms of both flow and chemistry. Having adequate estimates of mine discharge rates is vital for ensuring that the design of pumping and water treatment infrastructure is fit for purpose (Doe, 2014). We describe in this paper the application of the DFN method to a number of mine water studies: where the conventional REV approach is not appropriate due to scale; but permit the use of the DFN method to derive hydraulic properties; and the evaluation of heterogeneity.

The Discrete Fracture Network Method

The properties of individual, or discrete, fractures or similar features are explicitly described in a Discrete Fracture Network (DFN) model in order to allow the analysis of fluid flow (Dershowitz and Doe, 1988; Dershowitz and Miller, 1995; Dershowitz et al., 2011; Cottrell 2012). This approach is based on the principles of fluid flow in fractured media. A typical DFN model is shown at Figure 1. A DFN model of a dynamic system must include a representation of the existing natural fractures comprising not only the geometric and hydrological properties but also the geological and geomechanical properties of the three dimensional natural fracture network.

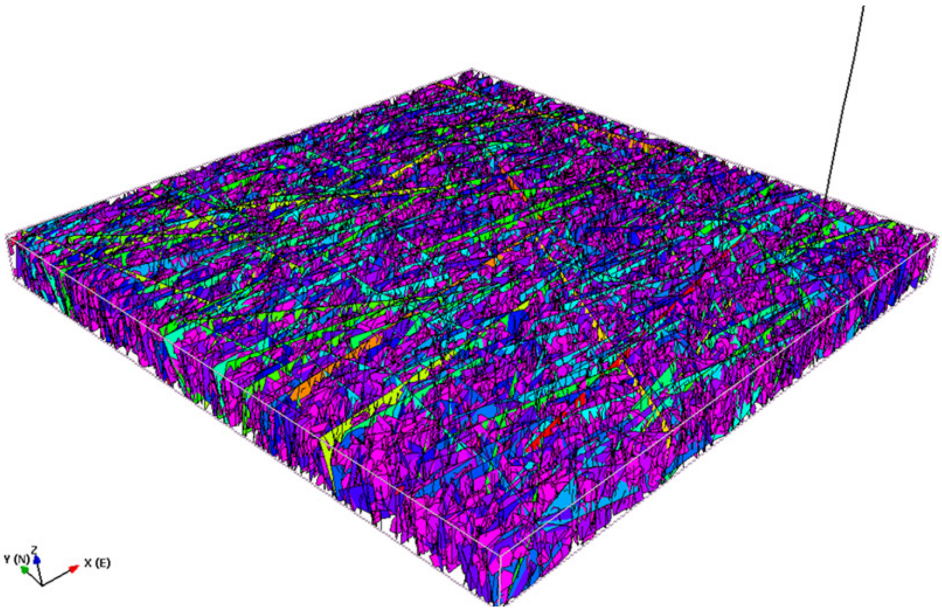


***Figure 1** Typical DFN model*

An example of the components of a DFN model, is presented at Figure 2. The geological data that describes the natural fracture network in terms of fracture orientation, intensity, and size is presented at Figure 2(a) to (c). Two significant fault structures, Figure 2(d), derived from geophysical data, are included in the full model (Figure 2(e)).

Fracture size is often a function of the mechanical stratigraphy and structural terminations. Fracture intensity may be stated either as a one-dimensional intensity (P10 -fractures/meter, along a specific sampling line), volumetric intensity (P32 – fracture area/volume) or as a fracture porosity (P33 – m3/m3). Volumetric intensity (P32) is most frequently used as it is not influenced by sampling bias due to the sampling direction, as with P10, or by aperture, as with P33.

The construction of a spatial model that describes how fractures are distributed in within the rock mass, and the inter-relationship between fractures, stratigraphy, lithology, and structure is the key to DFN modelling. Fracture orientations can be described using a number of statistical approaches, most typically a hemispherical probability distribution, such as Fisher or Elliptical Fisher, is used. Alternatively, fracture orientations can be linked to local geological factors, such as structural dip, structural position (e.g. on the axis of a fold rather than the fold limbs), Gaussian curvature, stress field, or seismic attributes. Typically, it is found that the key static fracture descriptors of orientation, size, intensity, and shape can be efficiently and effectively described using specific combinations of such attributes derived from multivariate regression analysis. The size of a fracture is stated as the fracture area and shape, often expressed as an "equivalent radius" of a circular-disk shaped fracture of equivalent area.

For hydraulic purposes in the DFN method each fracture is treated as a semi-confined aquifer – thus the hydraulic properties of fractures are transmissivity (kH) and storativity (S), which can be derived from generic or site specific correlations to available transient data (i.e. well test response), or if no such data is available then to fracture size, mechanical (apparent) aperture and transmissivity as well as sometimes to wireline geophysical data and other attributes.

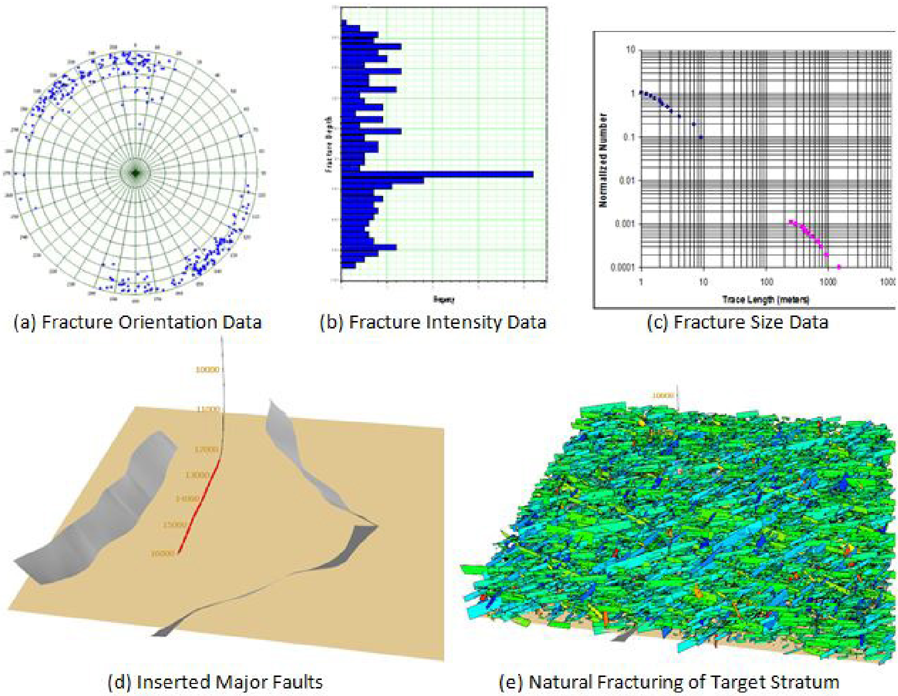


Figure 2 *Example of data for DFN model development including mapped major structures (d) and a stochastic representation of the natural fracture distribution (e)*

Mine Water Inflow

A DFN model was developed using Golder Associates' FracMan™ software to represent discrete inflows to an underground hardrock mine in North America. The model and approach are described in detail by Doe (2014) and summarised here. The purpose of the model was to enable an assessment of inflows to a planned extension to the mine. Both deterministic and stochastic features were included within the model. Deterministic features included water-bearing faults and veins whose locations are known. The remaining water-bearing fractures were treated stochastically, using probability functions to describe the main geometric and hydraulic properties of the fractures, including fracture intensity, size and orientation. Fracture orientation data was derived from oriented cores, mapping of faults in the mine and from the orientations of the known, major features such as faults (deterministic features). Fracture intensity was derived mainly from a survey of seepage points by mine staff. Fracture sizes were assumed to follow power-law distributions based on an analysis of trace maps of the deterministic features. The fracture transmissivity values were derived from a limited number of packer tests and a database of flow data from grout holes. Multiple realisations of statistically identical DFN fracture model were undertaken to provide a method for assessing potential model uncertainty.

The resultant model (Figure 3) was used to assess firstly the impact of an Aperture Controlled Grouting (ACG) programme, which can be successfully used to reduce groundwater inflow to the mine, and to enable an assessment of inflows to the mine during future development (Figure 4). This allows for effective planning of the management of mine inflows as development proceeds. As with all models, the results are non-unique and other realisations of a fracture network or a porous continuum could produce these same results. The DFN approach does however have the significant advantage of being able to incorporate and honoring the significant controlling geological features (Doe, 2014).

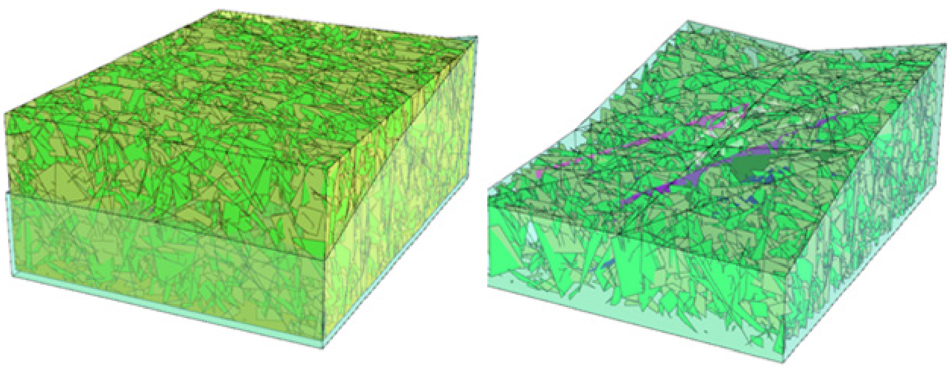
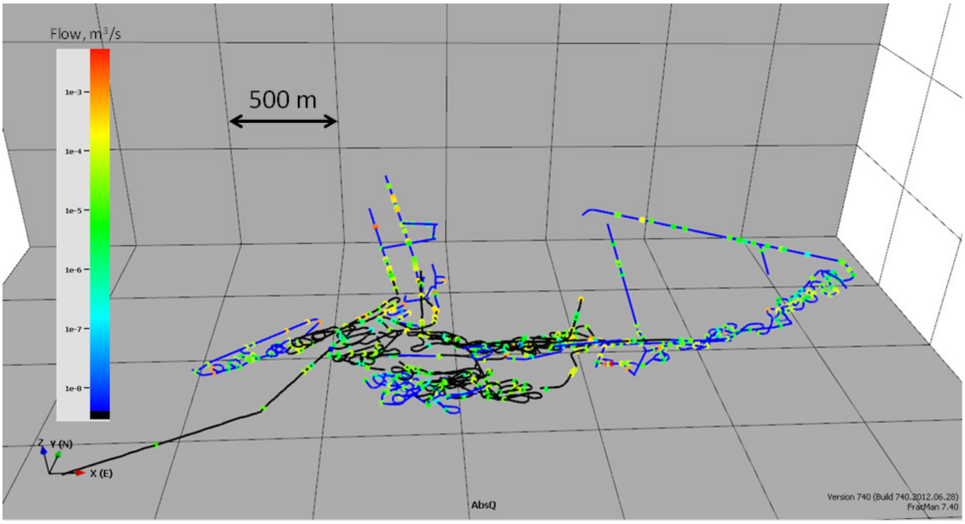


Figure 3 *DFN model of the mine area*



Black: existing tunnels; Blue: new development

Figure 4 *Simulated and Measured Seepage into existing a future development areas*

Derivation of Hydraulic Properties

In order to understand the impact of mine closure on the groundwater regime and on discharges from an operational underground polymetallic mine in the southern Caucuses region it was necessary to develop a hydrogeological model of the mine and its environs. The hydrogeological understanding of the mine is currently very limited and is based primarily on studies completed in the 1970s by hydrogeologists of the former Soviet Union. These studies were focused on collecting baseline geological information for the area rather than hydrogeological characterisation. Hence with the exception of some sparse groundwater level and chemistry data there is no hydrogeological data available with the exception of current estimates of discharge from the mine and flows in adjacent rivers. The underground workings sit beneath an area of land covering approximately 400 Hectares, and is accessed by more than 10 individual adits and 3 shafts. The geology comprises Middle Jurassic-age volcanogenic and sedimentary formations. The ore is hosted within metasomatised porphyritic andesite (flows, tuffs and pyroclastics) and volcanogenic conglomerates that are unconformably overlain by a sedimentary sequence of limestone, marls and volcaniclastic sandstone.

A DFN model was constructed (Figure 5) using the FracMan code to represent that fracture networks in the volcanic bedrock hosting the ore body based on fracture data (frequency, orientation and length) recorded in the Soviet mapping and more recent structural geology reports. The objective of the model was to characterise the possible range of hydraulic conductivity generated as a result of the observed fracture density and assumed fracture transmissivity. Reasonable estimates of fracture aperture were made based on field observations and correlations between fracture size and aperture (Dershowitz et al. 2003). Based on these datasets an upscaled equivalent porous medium (EPM) hydraulic conductivity dataset was calculated using a variation on the method of Oda et al. (1984) where isolated fractures are not included in the calculation. Whilst there is uncertainty in the results it does provide a basis for initial modelling that can be benchmarked against recorded mine discharges and river flows.

The results supported anecdotal information that: the permeability of the volcanic rock matrix is generally low; that inflows are largely restricted to identified fracture corridors; and that inflow to the mine is limited by bedrock permeability rather than the rate of recharge of precipitation to groundwater.

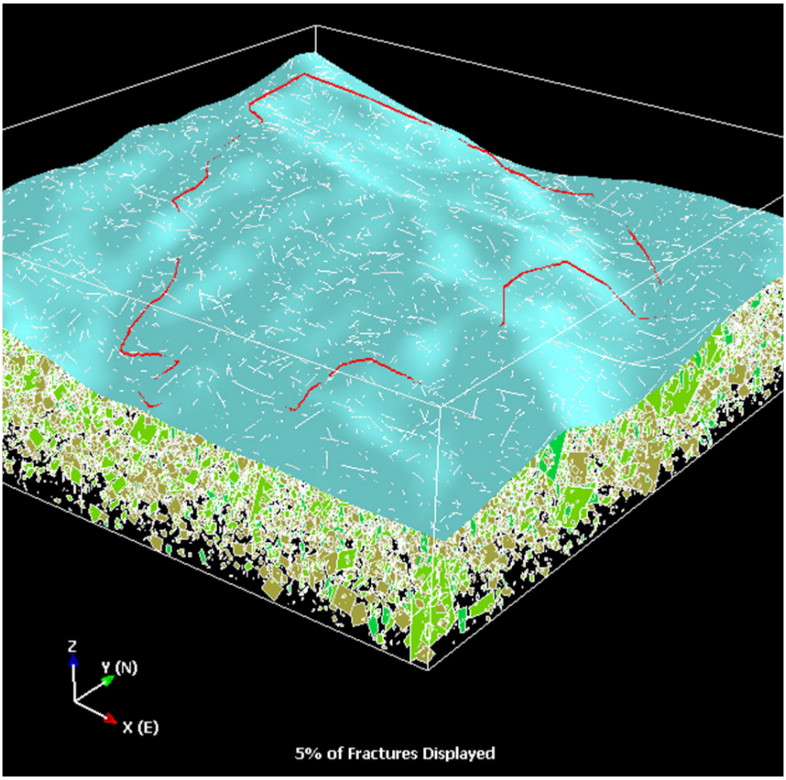


Figure 5 *DFN model of the volcanic bedrock in area around the mine*

Hetereogeneity

An area of uncertainty that often arises is the degree of heterogeneity in fractured strata, be they volcanic or metamorphic "basement" strata or limestones or fractured sandstones. The DFN method may be used to refine estimates of heterogeneity by considering the distribution of fractures (number of fracture sets, frequency, orientation etc.). An example of the use of this approach is as follows. A large dataset of hydraulic conductivity data was available for a fractured limestone aquifer, together with data regarding fracture characteristics from outcrop mapping, core logging and wireline geophysics (Figure 6). This data was used to update previously synthesised data published by Jones et al. (1999). The objective was to characterise the range of hydraulic conductivity within the area of interest including any variation with depth. An equivalent porous medium (EPM) continuum grid developed for the purpose of a distributed finite difference based flow models of groundwater movement in the area, was imported and for each cell an upscaled hydraulic conductivity (K) was calculated using the method of Oda. The resultant conductivity values (Kx, Ky and Kz) were then exported back to MODFLOW. The resultant hydraulic conductivity matrix confirmed the local dominance of vertical hydraulic connectivity as indicated based on geochemical evidence and the presence of zone of enhanced horizontal hydraulic conductivity, consistent with mapped geological structures.

A similar approach may be used to identify enhancements in hydraulic conductivity around pit walls due to blasting over break and interaction with existing geological structures. This can provide important direction to pit dewatering and in particular pit slope pore pressure management by allowing appropriate targeting of pit slope depressurisation wells.

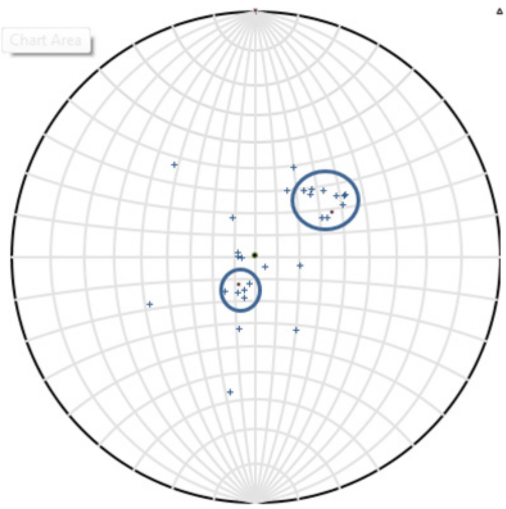


Figure 6 *Fracture azimuth and dip for a fractured limestone aquifer*

Conclusions

The examples above illustrate the application of the DFN to mine water studies and the associated benefits to hydrogeological characterisation both when detailed information is available to characterise and predict discrete inflows to mines, and to situations where data is sparse but existing geological and structural data sets may be used to build a hydrogeological understanding of a mine site. The examples illustrate the benefit of collecting data to characterise existing natural fractures as part of routine geological and hydrogeological studies.

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