# The importance of geotechnical characterisation and structural interpretation in predicting fracture flow to mines

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**Abstract** Multi-disciplinary investigations into proposed and existing mines present an opportunity for collaboration and sharing of both data and skill sets. This paper discusses the acquisition and interpretation of geotechnical and structural data and how it can be used in conjunction with hydrogeological investigations to more accurately predict groundwater flow within a mine environment. Geotechnical investigations can yield extremely useful information on fracture distribution and properties within the rock mass. However, these data are obtained at a local-scale and are often concentrated on the immediate vicinity of the mine, whilst most hydrogeological predictions must examine groundwater flow on a larger scale. Interpretation of local-scale fracture data in order to characterise the wider fracture network is not always straightforward. A sound structural interpretation based on geological, geomorphological and geophysical, as well as geotechnical data, can provide a framework in which to more accurately extrapolate local scale geometrical and hydraulic fracture properties to a regional scale. The results of geotechnical and hydrogeological investigations must; therefore, be integrated with a well-informed structural model in order to produce a more reliable prediction of groundwater flow to mines. Some examples of this process are discussed.

**Key Words** geotechnics, structural geology, structural interpretation, hydrogeology, fracture flow

## Introduction

The development of a mine from a concept through to a successful operation requires an understanding of groundwater, if present, and the potential implications this may have on: (a) inflows to the mine, and (b) the geotechnical stability of the mine. Unexpected or poorly managed inflows can at best reduce mining efficiency and at worst pose a severe threat to health and safety. Analytical and numerical methods for the quantitative prediction of fracture flow to mines can generally be divided into three categories – discrete fracture, dual porosity, and equivalent porous media (Odling, 1997). One of the major limitations of discrete fracture modelling is that normally only limited data on the in-situ fracture system exists and thus the geometry of the fracture system itself must be modelled. The large amount of data and modelling effort required for an average sized groundwater model makes this approach rare in all but the most small-scale mine dewatering problems. Dual porosity modelling is usually only applicable to a mine inflow prediction where the matrix exhibits significant permeability (rare in most ore hosting rocks) or when reactive transport modelling is required. By far the most common approach to mine inflow predictions is the equivalent porous media approach, which requires characterisation of the aquifer into discrete blocks with lumped hydraulic properties for which standard flow equations can then be solved. Aquifer characterisation in fractured rocks is complex as hydraulic properties may be lithologically and/or structurally controlled and may differ depending on the scale at which they are investigated (Bear, 1972; Bonnet et al., 2001). Reliable characterisation of the rock mass requires a combination of measured and determined properties over a range of scales. Measured fracture properties taken during a geotechnical investigation programme may yield valuable data on the fracture system at the borehole-scale. However, a structural interpretation provides the vital link between this local scale data and determined aquifer properties on the regional scale, providing the geometrical context to allow justifiable interpolation of the former over a scale more applicable to groundwater flow prediction. This process is often neglected in mine inflow predictions. This paper discusses the importance of both local and regional scale structural characterisation and interpretation of a fractured rock mass when considering groundwater inflows to mines.

## Geotechnical characterisation

Geotechnical characterisation of the rock mass is a fundamental requirement for the assessment of mine stability and the optimisation of mine design and operation. In terms of its contribution to the prediction of mine water inflows, geotechnical data may provide invaluable information on fracture system geometry (such as joint orientation, spacing, and persistence) as well as fracture properties (such as aperture, roughness, and infill). Logging of orientated drill core gives real-space fracture orientations which can be evaluated using stereonets to determine the prevalent fault and joint systems present. Such data is pre-requisite for derivation of a hydraulic conductivity tensor that accounts for anisotropy when applying groundwater flow equations to an equivalent porous media. Core logging also provides the opportunity to record joint conditions, aperture, and infill. These descriptions are invaluable to the process of hydrogeological characterisation as they allow the hydrogeologist to filter fracture data according to the likely permeability of the fracture fill material, as Figure 1 demonstrates. Figure 1 (a) shows a plane-to-pole stereonet of joint orientation in the footwall rocks of a proposed open pit mine based on all logged fractured orientations. Two dominant fracture sets can be seen which both dip to the south-east. Figure 1 (b) shows the same data but filtered for only those fractures which are open and clean or filled with coarse material. The filtered data highlights an additional northerly dipping fracture set that may play a role in groundwater flow, but which is lost in the unfiltered data.

Similarly, a log of fracture aperture derived from in-situ logging methods such as a downhole acoustic televiewer tool, can help to further filter geotechnical data for hydrogeological interpretation. Such data allow the hydrogeologist to place a higher level of significance on the orientation of larger (and likely more transmissive) fractures when deriving a hydraulic conductivity tensor.

One major limitation of borehole-derived geotechnical data is that it cannot easily provide information on the interconnectivity of the fracture system, a property which has a significant control on groundwater inflow to mines but which is difficult to measure as it can be independent of other measured fracture parameters. Theoretical techniques, such as percolation theory or statistical fracture network modelling, can be used to characterise fracture connectivity but these techniques are, at best, a mathematical approximation and depend heavily on appropriate data being collected at a suitable scale. Perhaps the biggest limitation of geotechnical data in terms of characterisation of fractured rock aquifers, however, is the scale of investigation. Fracture measurements are usually limited to scales less than a few tens of metres whereas most mine groundwater models must look at flow over a much larger area – typically over hundreds to thousands of metres. The question therefore arises as to how to upscale borehole-scale data such that groundwater flow can be characterised on the larger scale appropriate to most mine inflow problems.

## Structural characterisation

A sound structural interpretation plays a central role in the prediction of mine water inflows. It allows fracture properties logged from both geotechnical and exploration drilling campaigns to be intelligently extrapolated between boreholes based on a sound understanding of geological history and structural setting. In a fractured aquifer, fracture zones often reflect the field of strain surrounding, and closely related to, fault zones (Gudmundsson, 2000) such that mapping of faults is an essential pre-requisite for extrapolation of aquifer properties from point measurements. In the common case, where little to no outcrop occurs, the value of the structural model relies on the scope and quality of resource and geotechnical drilling programmes. Where brittle faults are common and the subsurface data are not oriented, fault interpretation can become a three-dimensional ‘join the dots’ exercise, where multiple outcomes are possible and the probability of getting the interpretation correct is low. The various data must be thoughtfully applied in order to derive a representative interpretation. Using oriented drillhole data can help to produce a more

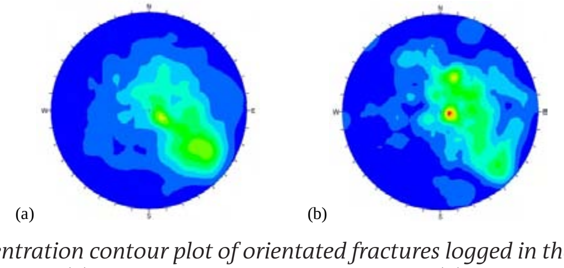


*Figure 1 Fisher concentration contour plot of orientated fractures logged in the footwall rocks of a proposed open-pit mine. (a) shows all orientated fractures and (b) shows the same data but filtered for open and clean or coarse fill fractures only*

reliable interpretation. Nevertheless, local measurements of fault orientations may be misleading as individual fractures may represent part of the complex internal structure of the fault zone rather than the principal fault surface. Additional important constraints can be placed on drill-hole-based fault interpretation by considering the thickness and nature of the faulted intervals during fault correlation. The length of the faulted interval and the nature of the faulted material, such as incohesive or cohesive breccia, gouge, shattered zones and cemented faults, can greatly assist in the correlation of intervals, which is of unparalleled importance when placing the structural evaluation in the context of groundwater flow. Regional to project-scale interpretation of major structures, using for example geological survey maps, geophysical data and remote sensing data, can provide a framework in which to interpret more detailed drillhole-based interpretations.

Although structural interpretations provide an essential contextual framework in which to understand geotechnical fracture data and hydrogeological test results, the role of structures in groundwater flow is not straightforward. This is illustrated by simply considering fracturing within a fault system. Figure 2 (after Bonson et al. 2004) shows a map of the Maghlaq Fault in Malta with fracture frequency at regular intervals along the fault zone shown as circles (scale is arbitrary). The high variability of fracture frequency along the fault trace, especially at discrete locations, can be clearly observed. The most intense fracturing occurs at structures identified as fault bends, branch-lines and relay zones. Although no direct permeability measurements were taken in this instance, the permeability along the fault line is likely to vary considerably. Clearly any structural interpretation; therefore, must consider the potential for heterogeneity in fracture properties within the same fault, as well as between fault influenced and non-fault influenced zones. It follows that faults should not be considered as convenient boundaries or homogeneous preferential flow paths in groundwater models unless these assumptions are justified with the relevant structural and hydrogeological data.

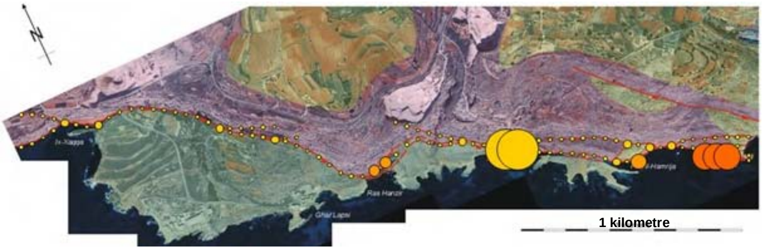


***Figure 2*** *Map of the Maghlaq Fault, a south-dipping normal fault in SW Malta (after Bonson et al. 2004). Circles represent the cube of relative fracture frequency (scale is arbitrary)*

## Example of an integrated approach to mine inflow studies

A prediction of mine water inflows to an open pit was undertaken as part of a multi-disciplinary mine feasibility study for an open-pit iron-ore project in Northern Europe. The site is located within variably fractured meta-sedimentary deposits dipping at around 50°. The conceptual approach taken for data collection, analysis, and characterisation of groundwater is summarised in Figure 3. Orientated diamond drilling was used to drill a series of geotechnical holes, the locations of which were a compromise between geotechnical and hydrogeological requirements. An acoustic televiewer tool was used in conjunction with manual logging to characterise the local scale fracture properties and single packer and impellor flowmeter tests were undertaken to derive permeabilities over discrete intervals. Once complete, piezometers were installed in the geotechnical holes and separate pumping wells drilled in order to undertake multi-day pumping tests at three test sites.

Geotechnical logging data were filtered according to fracture fill and aperture, which showed the orientation of many larger aperture, open fractures in the hanging wall rocks to differ from that of the main direction of fracturing, which generally followed bedding. Water strikes were found to correspond well with areas of high fracture frequency and RQD which, when combined with fracture aperture and packer and flowmeter data, allowed the key flow horizons to be identified and characterised. Hydraulic conductivity tensors were derived for some initial zones with apparent similar physical and hydraulic properties. A structural interpretation of the site was undertaken based on measurements from the resource, geotechnical, and hydrogeological programmes as well as remote sensing and magnetic survey data. The existence of four significant

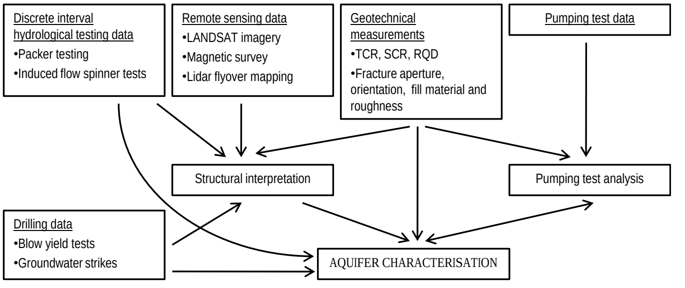


***Figure 3*** *Flow diagram showing an example multi-disciplinary approach to data collection and interpretation for aquifer characterisation as part of a mine water inflow study*

faults was confirmed with a reasonable degree of accuracy. One of these faults was found to be consistently filled with clay gouge at several points along its length. This was confirmed by packer test results which showed the permeability to be repeatedly lower than the surrounding rock mass. The other three faults were characterised as lineaments of relatively higher permeability. This structural interpretation was used to refine the hydrogeological characterisation of the site, which in turn was used to define an appropriate solution for the pumping test data, with geotechnical measurements such as fracture frequency required as input data. Results from pumping test analysis were used to further refine the aquifer characterisation.

Bulk aquifer properties were used in conjunction with other hydrological data to develop a conceptual groundwater model, which was used to derive both an analytical and numerical model of steady-state groundwater inflow to the final open-pit design. The numerical model produced significantly lower inflow predictions, which was attributed to the ability to incorporate aquifer anisotropy and linear flow features. Without the incorporation of geotechnical and structural evidence into the conceptual hydrogeological model, predictive modelling would not have incorporated some essential controls on groundwater flow leading to inaccuracies in the estimated mine inflows.

## Conclusions

The authors' experience working on mine water flow problems has highlighted that no single investigation technique is sufficient, on its own, to achieve an accurate characterisation of a fractured rock aquifer for prediction of inflows. Fractures range in size from microns to kilometres and hydrogeological characterisation should duly cover a range of scales. Local scale measurements of physical and hydraulic fracture properties derived from geotechnical drillhole data require a sound structural interpretation for extrapolation to a larger scale more applicable to mining groundwater flow problems. A structural interpretation should also be used as the basis for analysis of larger scale hydraulic testing such as pumping and tracer tests. Using both measured and determined properties over a range of scales permits a far more reliable prediction of groundwater flows to be made.

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