Assessing Geological Controls on Fracture Orientation and Intensity For Discrete Fracture Network Modeling

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Discrete fracture networks (DFNs) are an ideal way to characterize systems of foliations, joints, and faults in crystalline rock. The DFN allows for the representation of structural data in terms of statistical distributions, which can then be used for evaluation, prediction, or as input to other models. Golder Associates, through the fracMan software suite, has been successfully completing DFN projects for nuclear, oil and gas, and civil engineering projects for more than 20 years. This paper describes the results of DFN model development in support of the Swedish Nuclear Fuel and Waste Agency (SKB), which is developing a high-level nuclear waste repository for the country’s spent fuel reprocessing.

SKB is using the fracDFN approach, both at the site characterization efforts and to develop performance assessment models for repository licensing, for three candidate sites in Sweden: the Simpevarp and Laxemar sites within the province of Småland, and the Forsmark site in the province of Uppland. Both proposed sites are underlain by Precambrian-age igneous and metamorphic rocks of the Fennoscandian Shield. Predominant lithologies at the proposed sites are granite, diorite, and gabbro, and the Transcaucassian Ignimbrite Basalt (~1.8 Ma).

The DFN model is used to quantify and test assumptions regarding the orientations, sizes, spatial distribution, intensity, and deformation history of rock structures at multiple scales. The end product is a statistical description of geologic structures that can be used directly for tunnel design calculations, reservoir characterization, flow analysis, rock block / key wedge analysis, and confinement transport simulations.

The DFN model can be used to simulate equivalent porous media (EPM) blocks for reservoir-scale flows and to combine the regional-scale flow and transport codes such as MODFLOW or SEIBM.[1] In both the Laxemar and the Forsmark project regions, the DFN model was combined with a regional structural and a tectonic domain model to fit the combined geological framework for the entire volume of interest using seismic, geophysical, and geomechanical data.

The DFN model incorporates feedback of both the rock domain and the tectonic models, and helps to guide future studies by identifying areas of interest, assessing data gaps, and, to an extent, helping to quantify uncertainty for systems-scale models.

The first step in building the DFN was to group joints, faults, and deformation zones into local sets and to assess whether any regional patterns were visible, and what affect lithology had on joint / fault orientations.

Fracture orientation data was obtained from several sources:
- Borehole core and image logs
- Detailed outcrop and structural map line maps
- Geophysical and air photo lineament maps

Fracture set orientation data were divided on joint orientations in outcrop and the orientations of identified sets of related structures. These consistent fracture sets were plotted across the entire model region, with several outcrops possessing some less-intense sub-vertical and sub-horizontal local fracture sets.

Fracture set orientations were quantified through statistical probability distribution functions, which describe a fracture set in terms of its mean pole vector (p, q, r) and a dispersion vector (u, v, w). Laxemar DFN models utilize a Universal Fisher distribution with set assignments based on a hard-sector division algorithm implemented in the fracMan/DFN tools (Golder Associates). A combination of local-scale (1-10 meter) detailed outcrop map data and regional-scale (1000 m +) deformation zone traces were used to develop a size model for the Laxemar DFN. This model was used to provide a variety of probability distributions for scale data were tested for use, size analysis suggested that a power law distribution, of the form:

\[ f(x) = x^{-1} \quad \text{where} \quad x > 2 \quad \text{and} \quad y > 1 \]

worked the best to recast trace lengths obtained in outcrop from the three identified regional fracture sets. The fundamental assumption behind the use of a power-law scaling relationship is that a small subset of fractures represent most of the area in the outcrop (representing a ‘catastrophic’ set), with the regional scale deformation sets at the opposite end. Set members at all scales (outcrop fractures, faults, and deformation zones) were considered to be randomly distributed, and fracture intensity is currently being tested through a series of model simulations (1000 – 3000 m ground geophysical surveys conducted earlier this season but not yet analyzed).

The power-law size analysis involves determining scaling factors for a distribution of trace lengths measured in outcrop and the regional deformation zones. The trace length scaling parameters (\( \alpha \) and \( \beta \)) were determined by creating an anisotropic trace length frequency plot for each regional fracture set within each rock domain, with the intensity of any statistical rounding was carried out for both Euclidean and fractal intensity scaling assumptions. Once the cumulative frequency distribution is calculated, the intensity can be calculated for each fracture set in each geologic domain for any specified minimum and maximum fracture size (radius).

During the development of the Laxemar DFN model, the intensity of fracture network models (DFN) for the location of interest is defined as the number of fractures per unit area and is generally not observed in the model region. In the model region, fracture intensity generally increases with depth.

The process of developing discrete-fracture network models for the Laxemar area sites in support of repository licensing efforts directly link to establishing feedbacks between rock fracturing and geologic conditions:
- 1) Near-surface stress relief results are significantly so observed in the model region. Intensity normally increases with depth.
- 2) Lithology appears to have little effect on the orientations of fractures at the outcrop/ borehole scale or at the regional (deformation zones) scale within the Laxemar model domain.
- 3) Fracture set orientations appear to be highly variable with depth; this was an unexpected result from the model development.
- 4) The higher the degree of rock alteration/weathering, the greater the fracture intensity and the higher the ratio of open (transmissive) to sealed fractures. This effect is more prominently observed in the sites.
- 5) Overall variations in open and sealed fracture intensity outside of deformation zones is not well understood. Our analyses suggest that only 10% - 20% of the total fracture intensity can be explained by lithology and degree of alteration.
- 6) The critical uncertainty in the model is whether there is a continuum of fracture intensity from tens of meters to kilometers, or whether there are significant ‘gaps’ in fracture sizes. This uncertainty is currently being investigated through geophysical surveys.

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References:
- [1] Note: Detailed references for information presented in this poster are available upon request.

http://fracman.golder.com
http://www.skb.se