Flow channelling and transport pathways in discrete fracture networks with internal fracture heterogeneity

A. Frampton[1,2], and J. D. Hyman[3] and L. Zou[1,4]

[1] Department of Physical Geography, Stockholm University, SE-106 91 Stockholm, Sweden
[2] Bolin Centre for Climate Change, Stockholm University, SE-106 91 Stockholm, Sweden
[3] Computational Earth Science (EES-16), Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, New Mexico, USA
[4] Department of Sustainable development, Environmental science and Engineering, Royal Institute of Technology, SE-100 44 Stockholm, Sweden

Abstract

Analysing flow and transport in sparsely fractured media is important for understanding how crystalline bedrock environments function as barriers to transport of contaminants, with important applications for subsurface repositories for long-term storage of spent nuclear fuel. Crystalline bedrocks are particularly favourable in this context due to their geological stability, low advective flow and strong hydrogeochemical retention properties. The natural geological environment can thereby delay transport of radionuclides, allowing decay to significantly limit release to the biosphere. There are however many challenges involved in quantifying and modelling subsurface flow and transport, especially in fractured media, largely due to geological complexity and heterogeneity, where the interplay between advective and dispersive flow strongly impacts both inert and reactive transport. A key to modelling transport in a Lagrangian framework involves quantifying pathway travel times and the hydrodynamic control of retention (Frampton and Cvetkovic, 2011), and both these quantities strongly depend on heterogeneity of the fracture network.

In this contribution, we present recent analysis of flow and transport considering fracture networks where individual fractures are ascribed heterogeneity using multivariate normal distributions with different connectivity classes but where critical statistical properties of the fields are preserved. Specifically, we apply the random field generation method described by Zinn and Harvey (2003) to create a coherent triad of fields with near-identical correlation lengths and variances but which greatly differ in structure, corresponding to textures with well-connected low, medium and high permeability values. The texture with well-connected medium permeability values corresponds to a classical multi-Gaussian texture, the field with well-connected high permeability values correspond to a texture which is connected by channels of high permeability, and the field with well-connected low permeability values to a texture which is essentially disconnected by channels of low permeability.

We use the recently developed novel numerical discrete fracture network model DFNWorks (Hyman et al., 2015) to investigate how the different connectivity structures influence flow dispersion and channelling effects in networks of fractures. By considering multiple scales in a stochastic setting we quantify the relative impact of texture correlation length and connectivity class against network topological measures such as fracture intersection frequency, network connectivity and scale, and identify key thresholds for cases where flow dispersion is controlled by internal fracture heterogeneity versus network-scale heterogeneity. Thereby we highlight cases for which the assumption that internal fracture variability notably increases flow channelling compared to assuming effectively homogenous properties, and which in turn impacts the distribution of travel times and plume residence times. Furthermore, we also highlight enhanced flow channelling for cases where correlation structure continues across intersections in a network, and also relate these to network topological measures in a quantitative setting. Finally, we discuss application to realistic fracture networks using field data of sparsely fractured crystalline rock from the Swedish and Finnish candidate repository sites for spent nuclear fuel.

References

Frampton, A. and Cvetkovic, V. (2011) ‘Numerical and analytical modeling of advective travel times in realistic three-dimensional fracture networks’, Water Resources Research, 47(2). W02506. doi: 10.1029/2010WR009290.

Zinn, B. and Harvey, C. F. (2003) ‘When good statistical models of aquifer heterogeneity go bad: A comparison of flow, dispersion, and mass transfer in connected and multivariate Gaussian hydraulic conductivity fields’, Water Resources Research, 39(3). doi: 10.1029/2001WR001146.

Hyman, J. D. et al. (2015) ‘dfnWorks: A discrete fracture network framework for modeling subsurface flow and transport’, Computers & Geosciences, 84, pp. 10–19. doi: 10.1016/j.cageo.2015.08.001.