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Author(s):
Brixel, Bernard; Jalali, Reza; Klepikova, Maria; Loew, Simon

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Joint-analysis of single and cross-borehole hydraulic pressure transients to characterize the hydraulic properties and connectivity of fractured networks

Bernard Brixel, Mohammadreza Jalali, Maria Klepikova, and Simon Loew
Institute of Geology, Chair of Engineering Geology, ETH Zürich, Switzerland

Developing new in-situ approaches to characterize the hydraulic properties of discontinuities in a rock mass, ranging from individual fractures to complex fracture networks, is essential to improve our understanding of flow and transport processes in heterogeneous media and to further develop our ability to accurately model flow, solute and heat transport therein. Likewise, characterizing the nature and degree of hydraulic connection between intersecting fractures – where the bulk of fluid flow, mass and energy transport is generally constrained to a limited number of preferential flow paths – remains to date a difficult task to perform in the field, leaving therefore significant uncertainty in delineating the geometrical arrangement of such flow paths.

We present in this study a detailed analysis of high-resolution pressure transients, obtained from a series of single and cross-borehole hydraulic packer tests completed as part of the In-Situ Stimulation and Circulation (ISC) experiment conducted at the Grimsel Test Site (GTS), an underground rock laboratory located in the Aar massif in the central Swiss Alps. Using a network of six boreholes, drilled across two major sub-vertical shear zones and equipped with multi-packer systems to isolate the main fractures mapped, we completed in total 119 injection tests – including pulse tests, constant rate and periodic injection tests – to characterize hydraulic conditions across a network of 18 discrete monitoring intervals, ranging from 2 to 12.5 m in length and separated by inter-borehole distances between 6 to 36 m. Based on field data, we aim to investigate the interplay between the spatial heterogeneity in hydraulic properties and the observed cross-borehole connectivity patterns by jointly-analyzing transmissivity and storativity estimates with the pressure responses and arrival times of hydraulic signals observed during cross-hole tests. Preliminary results reveal a large variation in transmissivity estimates from single-hole tests, log-normally distributed around 10-8 m2/s and ranging from approximately 10-13 m2/s in moderately fractured intervals to 10-6 m̃2/s for the most transmissive fractures. Between boreholes, we observe that the diffusion of hydraulic signals through interconnected fractures takes place in a matter of tens of seconds up to about 50 minutes, yet tends to be attenuated due to the moderate transmissivity or possibly high storativity of fractures, and/or limited number of direct hydraulic connections. Only a few test intervals appear to have intersected a fractured zone with a high hydraulic diffusivity where strong pressure signals can propagate across the volume investigated. We also observe a lack of reciprocity between most permeable test intervals, both in terms of arrival times and pressure magnitude of hydraulic signals, which we hypothesize is the result of spatial variations in the transmissivity and storativity of fractures in combination with complex flow path geometries. We plan to further investigate these field results through synthetic experiments, using a discrete fracture network (DNF) modeling approach.