Simulation and Uncertainty Analysis of Nuclide Transport Breakthrough in DFN

Understanding the transport of nuclides in fractured rocks is crucial for ensuring biosphere safety, as geological barriers serve as the final line of defense against nuclide transport. In this study, I constructed a discrete fracture network (DFN) model based on authentic data from the prototype repository at the Äspö Hard Rock Laboratory (HRL) in Sweden. The model was used to simulate nuclide transport using particle tracking methods and to investigate the spatio-temporal evolution following nuclide leakage. The DFN model provides detailed fracture characteristics, enabling more precise predictions. To ensure accurate risk assessment, it is necessary to consider parameter uncertainty for the additional parameters. A Sobol variance decomposition global sensitivity analysis was conducted to quantify the impact of fracture parameters on flow rates, transport distances, and parameter interactions.

The probability distribution curves for both the breakthrough time and transport distance of nuclides exhibit approximately normal distributions. The initial breakthrough time is estimated to be 4.19 years, and the shortest transport distance is 187.392 meters. Initial transport is dominated by hydraulic gradient. Later, the effect of dispersion increases, leading to a pronounced heterogeneity in nuclide distribution and the emergence of retention zones and preferential flow phenomena.

Aperture is identified as the most influential parameter affecting transport distance, with a total sensitivity index of 0.687. It primarily modulates nuclide transport distance through changes in flow rates. Longitudinal dispersivity and aperture have a strong interaction, with a sensitivity index of 0.386, which greatly enhances nuclide transport. Three-dimensional fracture density and fracture dip angle exhibit total sensitivity indices of 0.183 and 0.185, respectively.The average fracture dip angle parameter input into the model promotes the formation of preferential flow or stagnant water zones by influencing fracture intersections within the network, thereby either facilitating or inhibiting nuclide transport and enhancing uncertainty regarding breakthrough times. These research findings provide scientific underpinnings and technical support for the accurate simulation and prediction of nuclide behavior within natural barriers.

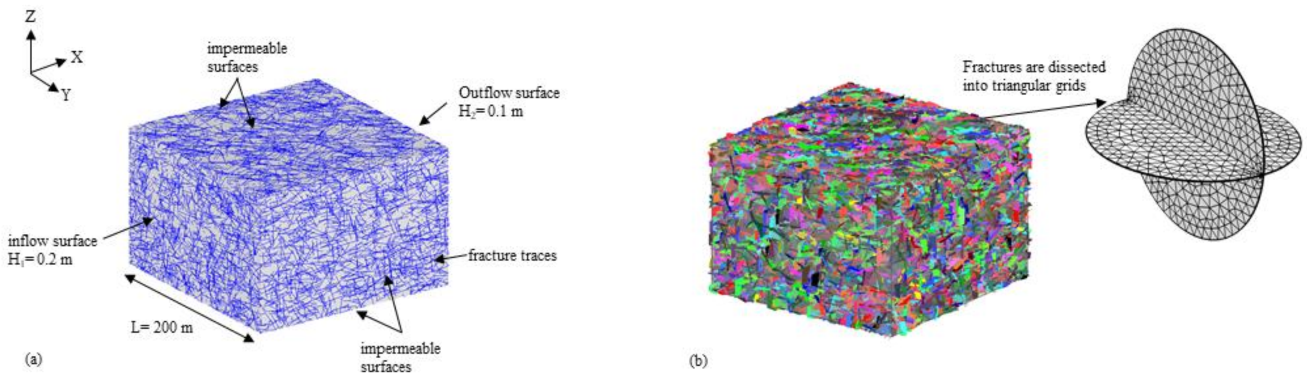

Fig.1. (a) the surface trace and boundary condition setup of the Äspö HRL 3D DFN model (b) triangular meshes of the dissected fracture network.

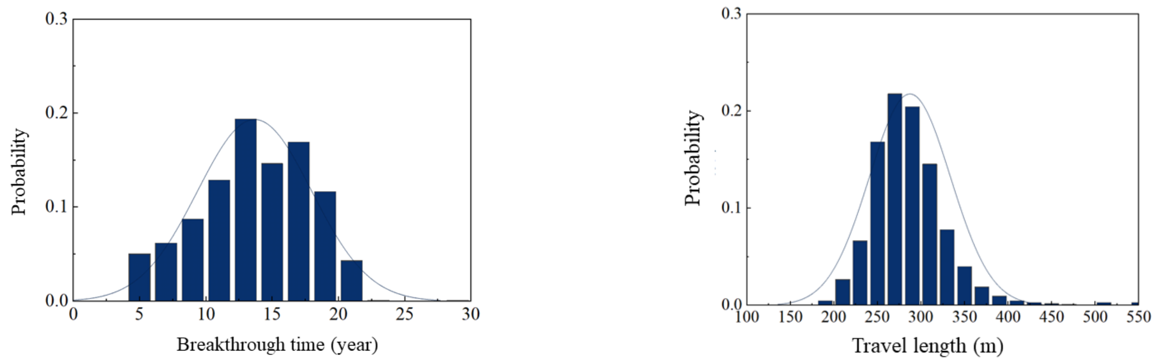

Fig.2. Probabilistic statistics of 3171 nuclide particles breakthrough time and travel length

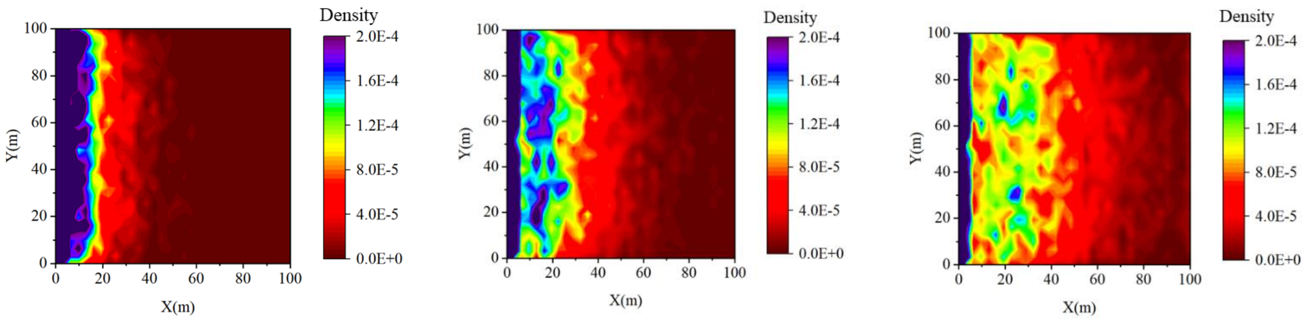

Fig.3. Density distribution of nuclides in the XY plane separately after 1, 7, and13 years of travel

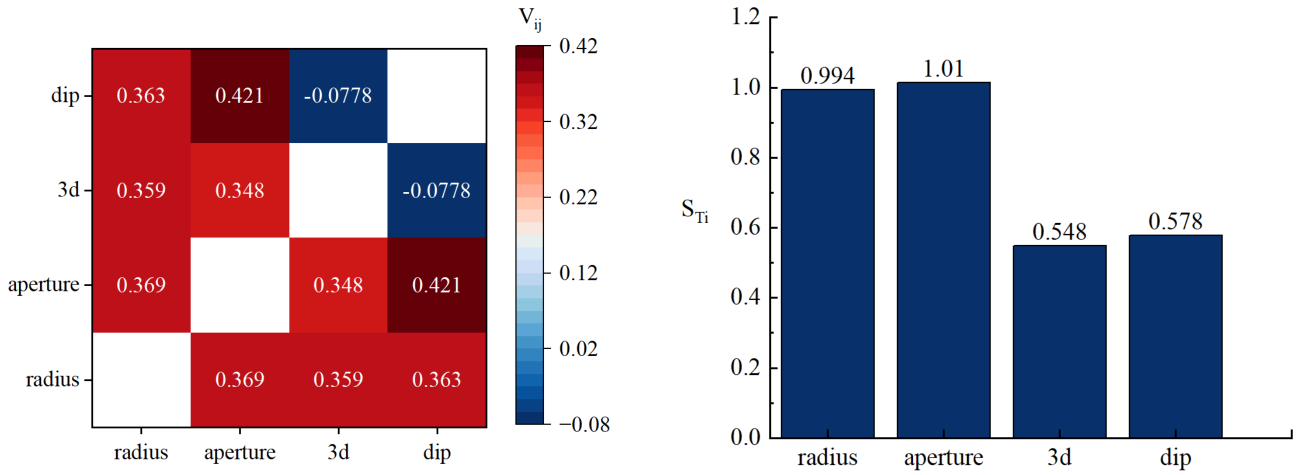

Fig.4. Second order sensitivities (Vij) and total sensitivities (STi) of the parameters to flow rate

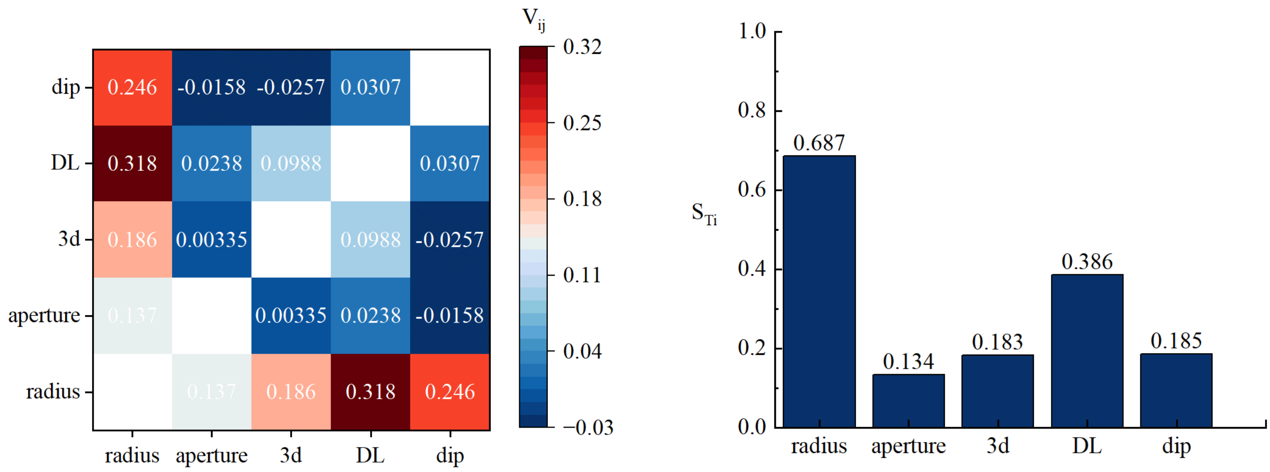

Fig.5. Second order sensitivities (Vij) and total sensitivities (STi) of the parameters to flow rate