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Inclusion-based effective medium models for the field-scale permeability of 3D fractured rock masses

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Fractures that are more permeable than their host rock can act as preferential, or at least additional, pathways for fluid to flow through the rock. The additional transmissivity contributed by these fractures will be of great relevance in several areas of earth science and engineering, such as radioactive waste disposal in crystalline rock, exploitation of fractured hydrocarbon and geothermal reservoirs, or hydraulic fracturing. In describing or predicting flow through fractured rock, the effective permeability of the rock mass, comprising both the rock matrix and a network of fractures, is a crucial parameter, and will depend on several geometric properties of the fractures/networks, such as lateral extent, aperture, orientation, and fracture density.

This study investigates the ability of classical inclusion-based effective medium models (following the work of Sævik *et al., Transp. Porous Media*, 2013) to predict this permeability. In these models, the fractures are represented as thin, spheroidal inclusions, the interiors of which are treated as porous media having a high (but finite) permeability. The predictions of various effective medium models, such as the symmetric and asymmetric self-consistent schemes, the differential scheme, and Maxwell's method, are tested against the results of explicit numerical simulations of mono- and polydisperse isotropic fracture networks embedded in a permeable rock matrix. Comparisons are also made with the Hashin-Shrikman bounds, Snow's model, and Mourzenko's heuristic model (Mourzenko *et al., Phys. Rev. E,* 2011).

This problem is characterised mathematically by two small parameters, the aspect ratio of the spheroidal fractures, α, and the ratio between matrix and fracture permeability, κ. Two different regimes can be identified, corresponding to $\alpha/\kappa < 1$ and $\alpha/\kappa > 1$. The lower the value of α/κ, the more significant is flow through the matrix. Due to differing flow patterns, the dependence of effective permeability on fracture density differs in the two regimes. When $\alpha/\kappa > 1$, a distinct percolation threshold is observed, whereas for $\alpha/\kappa < 1$, the matrix is sufficiently transmissive that a percolation-like transition is not observed.

The self-consistent effective medium methods show good accuracy for both mono- and polydisperse isotropic fracture networks. Mourzenko's equation is also found to be very accurate, particularly for monodisperse networks. Finally, it is shown that Snow's model essentially coincides with the Hashin-Shtrikman upper bound.