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Macro-permeability distribution and anisotropy in a 3D fissured and fractured clay rock: 'Excavation Damaged Zone' around a cylindrical drift in Callovo-Oxfordian Argilite (Bure)

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ABSTRACT

The Underground Research Laboratory at Bure (CMHM), operated by ANDRA, the French National Radioactive Waste Management Agency, was developed for studying the disposal of radioactive waste in a deep clayey geologic repository. It comprises a network of underground galleries in a 130 m thick layer of Callovo-Oxfordian clay rock (depths 400–600 m). This work focuses on hydraulic homogenization (permeability upscaling) of the Excavation Damaged Zone (EDZ) around a cylindrical drift, taking into account: (1) the permeability of the intact porous rock matrix; (2) the geometric structure of micro-fissures and small fractures synthesized as a statistical set of planar discs; (3) the curved shapes of large 'chevron' fractures induced by excavation (periodically distributed).

The method used for hydraulic homogenization (upscaling) of the 3D porous and fractured rock is based on a 'frozen gradient' superposition of individual fluxes pertaining to each fracture/matrix block, or 'unit block'. Each unit block comprises a prismatic block of permeable matrix (intact rock) obeying Darcy's law, crossed by a single piece of planar fracture obeying either Darcy or Poiseuille law. Polygonal as well as disc shaped fractures are accommodated. The result of upscaling is a tensorial Darcy law, with macro-permeability $K_{ij}(\mathbf{x})$ distributed over a grid of upscaling sub-domains, or 'voxels'. Alternatively, $K_{ij}(\mathbf{x})$ can be calculated point-wise using a moving window, e.g., for obtaining permeability profiles along 'numerical' boreholes. Because the permeable matrix is taken into account, the upscaling procedure can be implemented sequentially, as we do here: first, we embed the statistical fissures in the matrix, and secondly, we embed the large curved chevron fractures.

The results of hydraulic upscaling are expressed first in terms of 'equivalent' macro-permeability tensors, $K_{ij}(x, y, z)$ distributed around the drift. The statistically isotropic fissures are considered, first, without chevron fractures. There are 10,000 randomly isotropic fissures distributed over a 20 m stretch of drift. The resulting spatially distributed K_{ij} tensor is nearly isotropic (as expected). At the scale of the whole EDZ, the global $K_{FISSURES}$ is roughly 5000 times larger than permeability K_M. The detailed distribution of the equivalent $K_{FISSURES}(x, y, z)$ defined on a grid of voxels is radially inhomogeneous, like the statistics of the disc fissures. In addition, a moving window procedure is used to compute detailed radial profiles of $K_{FISSURES}$ versus distance (r) to drift wall, and the results compare favorably with *in situ* permeability profiles (numerical *vs.* experimental boreholes at Bure's GMR drift).

Finally, including the large curved chevron fractures in addition to the random fissures, the resulting $K_{ij}(x, y, z)$ appears strongly anisotropic locally. Its principal directions are spatially variable, and they tend to be aligned with the tangent planes of the chevron fracture surfaces. The global equivalent K_{ij} of the whole EDZ is also obtained: it is only weakly anisotropic, much less so than the local K_{ij}'s. However, because of the radially divergent structure of the 'chevrons' (although not quite cylindrical in geometry), it is recognized that the global K_{ij} due to chevrons lacks physical meaning as a tensor. Considering only the magnitude, it is found that the permeability due to 'chevrons' ($K_{CHEVRONS}$) is about 4 orders of magnitude larger than that due to statistical fissures ($K_{FISSURES}$), assuming a hydraulic aperture $a_{CHEVRON}$ = 100 μm. By a simple argument, $K_{CHEVRONS}$ would be only one order of magnitude larger than $K_{FISSURES}$ with the choice $a_{CHEVRON}$ = 10 μm instead of 100 μm. This significant sensitivity is due to several

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factors: the large extent of chevron fractures, the assumption of constant hydraulic aperture, and the cubic law behavior based on the assumption of Poiseuille flow.

The equivalent macro-permeabilities obtained in this work can be used for large scale flow modeling using any simulation code that accommodates Darcy's law with a full, spatially variable permeability tensor $K_{ij}(\mathbf{x})$.

1. Introduction

The Underground Research Laboratory at Bure (CMHM – Centre de Meuse/Haute Marne, France) is operated by ANDRA, the French National Radioactive Waste Management Agency. The purpose of the laboratory is to study the disposal of radioactive waste in a deep clayey geologic repository. The laboratory comprises a network of underground galleries through a 130 m layer of Callovo-Oxfordian "argilite", or clay rock, about 155 million years old, and located between 400 m and 600 m depth.

In this context, the present work focuses on the hydraulic homogenization (upscaling) of the Excavation Damaged Zone (EDZ) around a cylindrical excavation (gallery), taking into account the specific geometric structure of two sets of dicontinuities: (i) the 'fissures' comprising in fact microfissures as well as minor fractures (submetric) and (ii) the much larger curved shear fractures organized in a 'chevrons' pattern. The latter are induced by (ahead of) the excavation front, and have an extension of several meters. In addition, the permeability of the intact porous rock is also directly taken into account.

In summary, the 'damaged' heterogeneous medium is made up of three sets of conductors: (i) microfissures and moderate size fractures (submetric); (ii) large curved 'chevron' fractures (several meters); and (iii) intact porous matrix (undisturbed clay rock).

Two different geometric models are used for structuring the two sets of discontinuities in 3D space: (i) the 'fissures' are represented as a *statistically isotropic set of planar discs*; and (i) the 'chevron' fractures are represented as a *periodic set of curved parametric surfaces*.

The results of hydraulic upscaling (to be explained further below) are expressed mainly in terms of 'equivalent' *macro-permeability tensors*. The macro-permeabilities obtained in this work will be compared against *in situ* data, namely, permeability profiles along boreholes.

2. Geometric and statistical modeling of the 'EDZ' in 3D

In this paper, we consider a 3D stretch of a cylindrical excavation (gallery or drift), with the following geometry: (i) section length $L = 20$ m; (ii) drift diameter $D_{DRIFT} = 4$ m; (iii) thickness of the annular EDZ around the drift: $E = 4$ m. The chosen domain of investigation is a 3D rectangular box of size 20 m × 13 m × 13 m, which encloses the drift and its 'EDZ'.

The transverse scales for the drift and EDZ correspond roughly to the experimental drifts excavated at Bure and the observed EDZ. For convenience, the drift length was shortened from about 100 m to 'only' 20 m. This does not affect the 3D hydraulic upscaling study conducted in this paper, given the statistical homogeneity of the EDZ along the drift axis.

The goal of this section is to present a geometrical and statistical model of the 3D structure of the clay rock in the Excavation Damaged Zone (EDZ), on which the rest of the paper is based.

2.1. Statistical network of fissures (random plane discs)

The 'fissures' (microfissures and small fractures) are modeled as statistical set of planar discs, with randomly isotropic orientations, and radially decreasing density, diameters and apertures away from the drift wall : a visualization is shown in Fig. 1.

The main hypotheses for the statistical set of discrete fissures were:

- The fissures are plane discs with statistically isotropic orientations in 3D euclidian space.
- Their planar size is a random variable (random radius R or random diameter D).
- Their thickness or 'aperture' is a random variable (random aperture 'a').
- Their euclidian positions (X, Y, Z) are random: they follow a modified Poisson-type process such that the volumetric density of fissures (ρ_{03}) is radially inhomogeneous (decreasing)...

The volumetric density $\rho_{03}(r)$ expresses the number of discrete 'objects' per m^3 of euclidian space, as explained in Appendix A. This appendix provides a "*geometric probability*" analysis of radial inhomogeneity, and particularly, of the relation between volumetric density $\rho_{03}(r)$ and the Probability Density Function (PDF) of fissure centers positions (X, Y, Z).

Given our choices, as will be seen, $\rho_{03}(r)$ decreases quite fast with radial distance 'r' from the drift wall, and so does the mean fissure radius R and the mean aperture 'a'. These are maximal at the drift wall. For example:

- the maximum aperture of fissures (at the drift wall) is: $a_{MAX} = 5.0$ E − 5 m (50 μm);

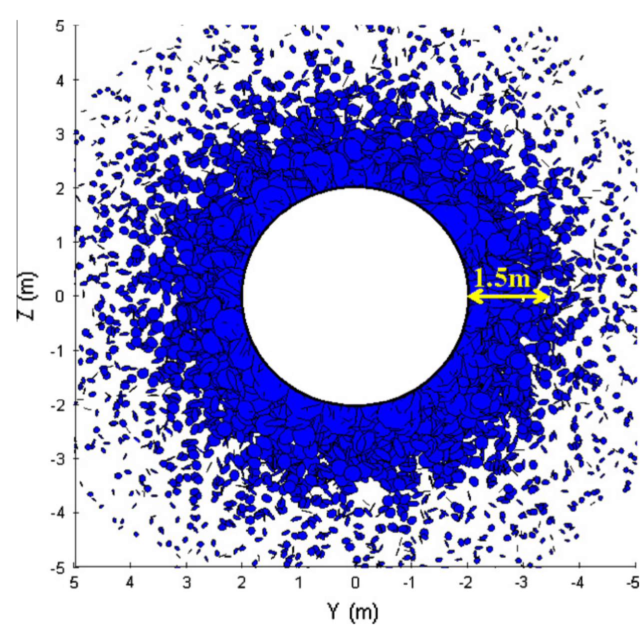

Fig. 1. Front view of the set of 10,000 planar disc fissures on the transverse vertical plane at the drift entrance (3D view with hidden parts). As can be seen, density and diameters decrease radially (so do the apertures, although they are not visible in this view).