Transition from Single- to Dual- or Multi-Continuum Model

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To simulate highly transient flow and transport effects, the exchange of water, heat, and solutes between the fractures and the matrix is important, and storage of fluids and components in the pore volume and heat in the solid rock grains needs to be accounted for.

Large faults or fracture zones should be discretely and deterministically included in the model, whereas the connected network of smaller fractures can be represented by a continuum approach, with interactions to the rock mass in between the fractures also simplified by lumping all the matrix volume into another, overlapping continuum. This method of overlapping but connected continua is referred to as a multi-continuum approach, with the classic double-porosity (Warren and Root, 1963) being a special case involving only two continua—one for the fracture network and one for the matrix—and without accounting for global flow through the matrix (i.e., global flow occurs only through the fracture continuum, with local fracture-matrix interaction). A model that also includes global flow through the matrix is referred to as a dual-permeability model, and a model in which the matrix continuum is further subdivided into multiple sub-continua, each referring to the rock mass at a certain distance from the fractures, is referred to as a multiple interacting continua (MINC) model. Details can be found in Appendix C of Pruess et al. (2012).[1]

It is essential to realize the transition from a single- to a multi-continuum model is solely accomplished by changing the geometrical information in the `ELEME` and `CONNE` blocks, and by providing appropriate material properties for the fracture-network and matrix continua in the `ROCKS` block. No change in the underlying mathematical model or numerical solution scheme is required. The transition is therefore simply a pre-processing step and mainly concerned with the geometric information in the mesh file.

The transition process starts with a standard single-continuum mesh; this mesh is referred to as the "primary mesh." The following steps are then executed:

(1) Each material type used in the primary mesh, which represents effective continuum properties) will be separated into a fracture and matrix continuum. For each material to be MINC processed, provide two additional materials—placed immediately following the original, single-continuum material in block `ROCKS`—and define appropriate fracture-continuum and matrix-continuum properties for this pair of materials.

[1] A MINC model is conceptually limited to considering global flow through the fracture network only (option `DFLT`), or a model with vertical fractures and global matrix-to-matrix flow in vertical direction only (option `MMVER`). Option `MMALL` leads to geometrically unreasonable connections between the matrix shells.

(2) Move all elements that are to be subdivided into multiple continua using the same fracture-network properties (see Step (3) below) to the top of the ELEME block.[2] Add a dummy element of zero or negative volume between the last of these elements and all the elements that should not be altered. These single-continuum elements will still be part of the model; at the interface to the multi-continuum region, they will be connected to two elements: the fracture-continuum element and the outermost matrix-continuum element.

(3) Set up a MESHM block in the TOUGH2 input file; see Appendix F of Pruess et al. (2012). Use keyword MINC, which initiates MINC processing of the active elements (those above the dummy element) in the rearranged primary mesh. The key parameters specified in the MINC block include information on the nature of the fracture distributions (number and relative orientation of fracture sets) and matrix-matrix connectivity (i.e., double-porosity or dual-permeability). The average fracture spacing within each of the fracture sets (see variable *PAR(I)*) is the key property affecting fracture-matrix interaction (affecting the nodal distances and interface areas between the fracture and matrix continua).[3] Variable *VOL(I)* holds the volume fraction for elements representing the fracture continuum and each of the matrix continua; these parameters directly affect the element volumes in the mesh file.[4]

(4) Use command ENDFI (instead of ENDCY) at the end of the input file containing the MESHM block with MINC specifications. Run (i)TOUGH2.[5]

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[2] This step can easily be accomplished using standard Unix/Linux commands, such as egrep, which extracts all lines from the primary mesh file that match one of the material names found in the argument list with the names of materials that need to be MINC processed. Once extracted and saved in a temporary file, these same elements can be removed from the ELEME block using command egrep -v (or using commands available in the vi editor, such as :g/material_name/d). The previously extracted elements can then be reinserted at the top of the ELEME block, followed by a zero-volume dummy element.

[3] Nodal distance and interface areas representing different continua are calculated internally based on the so-called proximity function, which depends on the fracture network geometry and thus the shape of the matrix blocks between the fractures. This approach provides great flexibility in representing various fracture network geometries using a continuum approach. For details, see Pruess (1983).

[4] As an example, let's assume fractures occupy 1% of the total reservoir volume; this is often referred to as the fracture porosity. In the numerical model, a volume fraction of 2% could be specified along with a fracture-continuum porosity of 50%—the porosity specified in block ROCKS—to arrive at the continuum-scale fracture porosity of 1%. Specifying a volume fraction (which determines the volume of the fracture element) that is larger than the fracture porosity has the advantage that changes in fracture porosity can easily be reflected by simply changing the fracture-continuum porosity in block ROCKS rather than changing *VOL(1)* in block MESHM, which requires that the mesh be regenerated. It also allows simulating heat storage and adsorption process in fracture infill material.

[5] If using iTOUGH2 under a Unix/Linux operating system, add command line argument -mesh, which instructs the script file *itough2* to return the primary and secondary (MINC) mesh files from the temporary to the working directory, with file extensions *.mes* and *.min*, respectively.

(5) The resulting, secondary mesh is called *MINC* (on PC) or has the input file name with the file extension *.min* added (on Macintosh and Unix/Linux platforms). Each element name starting with a blank character represents the fracture continuum, whereas each element starting with the number 2 (or greater, if more than one matrix continuum is requested) refers to the corresponding matrix continuum.

(6) Remove the dummy element from the resulting secondary mesh file.

(7) Repeat Steps (2) to (6) for each material that has its own fracture-network properties (see Step (3)).

The question arises whether it is sufficient to represent the rock mass between the fracture network with a single matrix continuum (i.e., a double-porosity model), or whether it must be further subdivided (to yield a MINC model) to improve the accuracy of the simulated fracture-matrix interaction. In general, the need for a MINC model increases if the time scale of interest is relatively short in comparison to the time needed for hydrological, thermal, transport, and reaction fronts to penetrate a significant portion of the matrix block. Consequently, a system with relatively large fracture spacings call for a higher resolution of the matrix.[6] Sensitivity analyses with respect to fracture spacing are relatively straightforward. While changing fracture spacing has no impact on the number of elements, changing the number of matrix continua is more involved and leads to considerably larger, computationally more demanding models.

References

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[6] Recall that if fracture spacing is very large, the continuum assumption underlying the MINC approach is likely invalid, and the fractures need to be explicitly discretized in a deterministic manner.