Identifying primary subnetworks in sparse three-dimensional discrete fracture networks using weighted graphs

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Abstract

We present a graph based method to identify the primary subnetworks in a three-dimensional fracture networks. The discrete structure of fracture networks naturally lends its self to using graphs to represent and characterize fracture network. The method incorporates topological, geometric, and hydrological properties of the fracture networks into graphs as edge weights. By finding the edge-disjoint shortest paths through the network we identify subnetworks where the fastest transport occurs without user controlled parameters or running flow and transport simulations.

Introduction

The structural heterogeneity of fracture networks results in irregular fluid velocity fields where flow channeling, isolated regions of high velocity, are commonly observed and indicates existence of primary subnetworks (also referred to as backbones). The macro-scale structure of the network, e.g., orientations and density, meso-scale hydrological attributes, e.g., fracture permeability [1] and the direction of flow [4] determine which fractures make up the primary subnetworks. These primary subnetworks tend to be a few larger fractures that are connected together by smaller fractures [2]. Removing all small fractures below a size threshold fails to identify the primary subnetworks because it can modify network connectivity and thus eliminate primary flow paths, which influences transport properties [5]. Moreover, which fractures are in the primary subnetworks depends on the direction of flow, something that geometrically based thresholding does not consider.

Hyman et al. [3] developed a graph-based method to identify primary subnetworks in sparse three-dimensional discrete fracture networks. In their method, each node in a graph corresponds to a fracture and and two nodes were connected if the corresponding fractures intersected. The discrete structure of fracture networks naturally lends its self to using graphs to represent and characterize fracture networks. Primary subnetworks identified by their method were subgraphs based on the k shortest loopless paths between the inflow to outflow boundaries, which corresponds to the fewest number of fractures through the domain. The number of paths included in the subgraphs depends on the scaling behavior of the number of edges in the graph with the number of shortest paths. However, the adopted mapping between DFN and graph prohibited the inclusion of geometric and hydrological properties, e.g., distances on fracture planes or fracture permeability. Moreover, it required that the network exhibited a scaling behavior with specific asymptotic behavior and that the user select the number of loop-less paths based on this scaling.

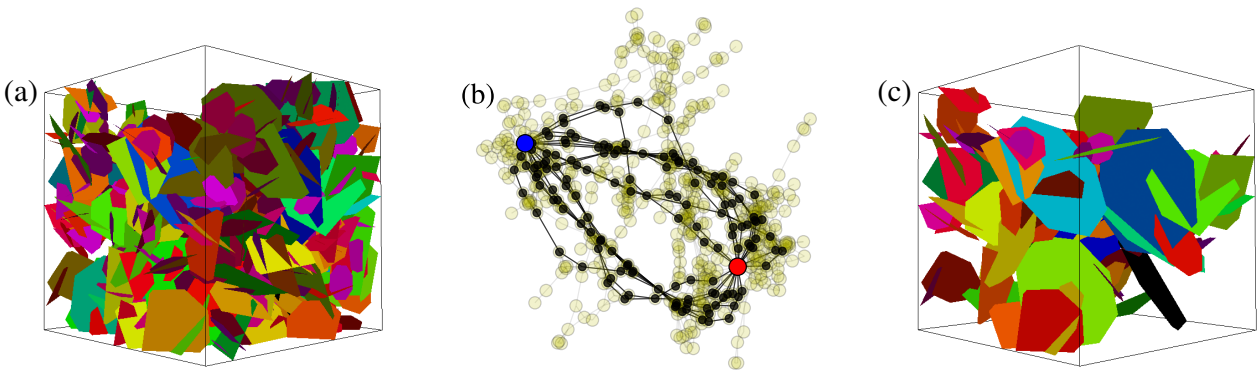

Figure 1: (a) A Sample DFN, (b) the graph associated with the DFN and the primary subgraph extracted using this method and (c) the corresponding subnetwork.

Methodology

We overcome these two primary limitations of the method presented in Hyman et al. [3]; namely the omission of geometric and physical attributes in the graph representation and the need to select the number of shortest paths k. The development of a different mapping between fracture networks and a graph representation allows us to include geometric and physical attributes as edge weights. We consider four different edge weights: unit weight, length between fracture intersections, hydraulic resistance (the reciprocal of permeability), and the product of the length between fracture intersections hydraulic resistance on that fracture. In turn, we can consider weighted shortest paths between the inflow and outflow boundaries that include topological, geometric, and hydrological properties. Furthermore, we present a method to extract primary subnetworks that does not have a user selected parameter. Figure 1 summarizes the methodology. Figure 1 (a) shows a DFN composed of around 500 fractures. Figure 1 (b) shows the graph associated with the DFN (yellow nodes) and the primary subgraph extracted using this method (black nodes and edges). Figure 1 (c) shows the subnetwork associated with primary subgraph shown in Figure 1 (b).

Results

Quality of the method is determined by computing and comparing transport on the primary subnetworks and the entire networks. In particular, we consider the first passage time through each network and the subnetworks. Figure 2 shows one-to-one comparisons of the first passage times in backbones identified using versus the first passage time through the entire network. Here we show results for the subnetworks identified using graphs with edge weights based on length times hydraulic resistance, which included topological, geometric, and hydrological information. Time has been non-dimensionalized by the median breakthrough time in the entire networks. Figure 2 (a) compares values of first arrival time for the unit-weight networks (b) length-networks (c) hydraulic resistance-networks and (d) In general, the comparisons are quite good, having high R^2 values and low RMSE values. On average, each subnetworks requires around 4 minutes for meshing, flow and transport, compared to the around 30 minutes for the entire networks.

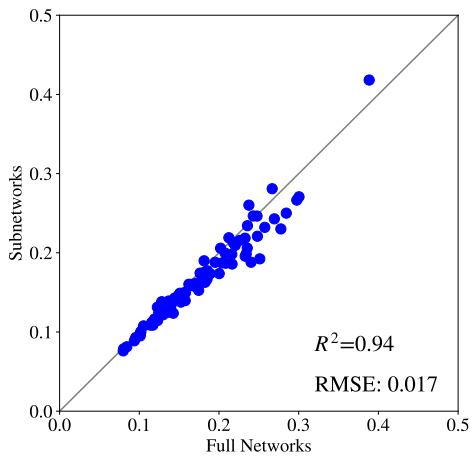

Figure 2: First passage times in subnetworks vs the first passage time through the entire network.

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