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A three-scale index for flow in karst conduits in carbonate rocks

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ABSTRACT

A three-scale model for flow in karst conduit networks in fractured carbonates is rigorously constructed based on a reiterated homogenization procedure. The first upscaling, performed from the high-fidelity flow model, is based on sequential partially and fully topological model reduction procedures considering two discrete networks of solution-enlarged fractures and conduits. The subsequent macroscopization procedure projects the reduced model into the cells of a coarse computational grid, where homogenized equivalent properties are numerically constructed. Such a two-level upscaling gives rise to a macroscopic flow model characterized by mass-transfer functions between the geological structures. A notable consequence of the approach proposed herein is the appearance of a new karst index concept, whose underlying physics relies on the generalization of the traditional Peaceman's theory of well index. Such a concept rules the mass exchange between conduits and matrix and can be extended to the general scenario of coupled flow in multi-branch karst conduit systems, displaying general non-circular cross sections and surrounding damage zones. The downscaling representation for the karst index can be further explored to improve accuracy of the exchange coefficient between the geological objects. Numerical experiments are carried-out showing the magnitude of the index for certain conduit and fracture arrangements, along with illustrating the impact upon flow patterns.

1. Introduction

Fractured and karstified carbonate reservoirs are extremely heterogeneous and exhibit pore spaces with different sizes, geometries, and connections, extremely difficult to characterize and predict in the subsurface (see e.g. Baomin and Jingjiang, 2009). The pore space is formed during primary sediment deposition followed by coupled deposition and burial which give rise to secondary porosity associated with these sediments (Moore, 1989). Karstification occurs during infiltration of aggressive fluids that dissolve the host rock (Palmer, 1991), which is mostly developed along fractures and sedimentary bedding in carbonate rocks, and is caused by fluids from the surface (epigenic karst) or ascending fluids from the subsurface (hypogenic karst) (Klimchouk et al., 2016). Such a complex scenario leads to the appearance of highly irregular dissolution structures in carbonate rocks, commonly referred to as karst systems, whose associated network, dominated by interconnected cave conduits, may provide pathways of high conductivity for localized flow. Such systems may also extend towards the surface through sinkholes and springs (Palmer, 1991). Throughout the manuscript, we adopt the karst terminology to designate a geologic environment characterized by the abundance of aqueous dissolution processes in underground conditions that propagate progressively through the host rock, mostly along a highly fractured, dissolutionally modified carbonate rock (Annable, 2003).

The macroscopic geobodies originated from karstification consist of coalesced cave passages, referred to as karst conduits, intertwined by a network of enlarged fractures and bedding planes (Loucks, 2007). The conduit network forms macropores and commonly exhibits self-organization features displaying long correlations in the permeability field which give rise to localized flow pathways (Saller et al., 2013). In this setting, pore systems may differ from each other by several orders of magnitude, giving rise to triple porosity/permeability systems (Worthington et al., 2000; Wu et al., 2011).

The classification of cave patterns was pioneered by Palmer (1991), who analyzed several thousands of cave passages and proposed different self-organized structures to describe epigenic (dissolution caused by meteoric fluids from the surface) and hypogenic karst (dissolution caused by ascending fluids from the subsurface) to represent the entire cave-network system (see Klimchouk et al., 2012 and references therein for an exhaustive review). In addition, Annable (2003) provided an exhaustive overview of the evolution of the conceptual models to describe the formation of karst systems. Among other effects, fracture density in the

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