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ORIGINAL PAPER

A new computational model for karst conduit flow in carbonate reservoirs including dissolution-collapse breccias

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Abstract

We construct a new computational model to describe coupled 3D/1D flow in carbonate rocks intertwined by a network of karst cave conduits. The proposed approach shows ability to incorporate pointwise velocity-dependent jumps in the pressure field arising from localized partial obstructions due to the presence of collapse-breccia within the discrete conduit network. At the microscale, we postulate single phase viscous flow governed by the Navier-Stokes equations in the conduit network coupled with Darcian flow in the rock matrix and supplemented by transmission conditions at the common interface. Subsequently, we proceed by constructing a sharper lower-dimensional reduced model wherein, in addition to the usual high geometric aspect ratio between the length and hydraulic diameter of the cave system, we introduce an additional small parameter containing the ratio between the localized width of the perturbed flow region, in the vicinity of each breccia, and characteristic length of the network. The asymptotic behavior gives rise to a coupled mixed-dimensional flow, where 1D sub-manifolds appear embedded in the 3D carbonate matrix with coupling ruled by a mass exchange line-source δ-function, acting synergistically with discrete non-linear pressure jumps of Robin type at the discrete set of breccia locations. The mixed-dimensional flow equations are discretized by a locally conservative extended version of the mixed-hybrid finite element method, showing capability of incorporating the new non-linear discrete transmission jump conditions between elements adjacent to the breccias. Computational simulations are performed for particular configurations of well/karst conduit systems, illustrating the influence of the karst and breccia upon the flow regimes, streamline patterns and well productivity.

Keywords Carbonates with karst cave conduits · Lower-dimensional model reduction · Collapse-breccia · Coupled 3D/1D flows · Non-linear Robin transmission condition · Hybridized mixed methods

Article Highlights

- A two-parameter asymptotic mixed-dimensional reduced flow system is derived to improve comprehension of the role of dissolution-collapse breccias in karst conduit carbonate rocks.
- The computational model is capable of handling complex karst-conduit geometries along with separated compartments adjacent to the collapse-breccias.
- The high-fidelity model based on the Navier-Stokes equation is explored to obtain further insight in the pressure jump conditions in the vicinity of collapse-breccias.
- A set of computational simulations of well/karst cave conduit scenarios with gradual increase in the number of conduits shows the influence of the karst and breccia upon well productivity index.

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1 Introduction

Soluble rocks, such as carbonates and evaporites, often exhibit complex heterogeneity patterns, compared to siliciclastic, and behave highly susceptible to form karst dissolution features at multiple scales when exposed to aggressive fluids [38, 40, 44, 45]. Conceptually, karst is a type of landscape engendered by hydrological and geomorphic mechanisms associated with several chemical, biological, thermal and mechanical phenomena [26]. Particularly, a relevant process governing the genesis of karst formations is dissolution induced by the downward movement of meteoric waters, forming epigenic karst [6], or by ascending hydrothermal fluids from the subsurface, giving origin to hypogenic karst

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