

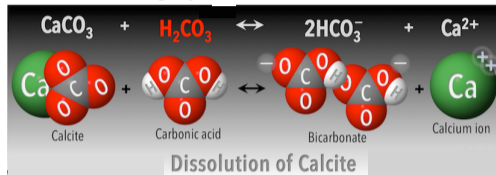
Model for Flow in Karstified Carbonate Reservoirs using Two-Level Upscaling and Surrogate-Based Transmissibilities under Geomechanical Effects

Patrícia Pereira,
Tayná Lobo,
Josué Barroso,
Emanuel Gomes



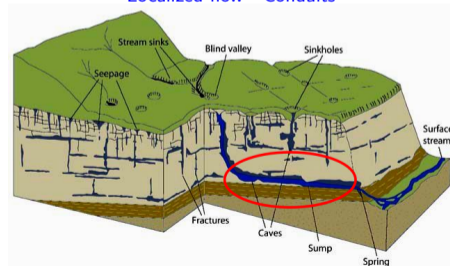
1. Motivation
2. Literature Review
3. MsEDKM
4. MsEDKM coupled with Geomechanics
5. Computational Results
6. Wrap-up

- Sedimentary carbonate rocks are highly reactive to fluids



- Dissolution processes \implies karst:
vugs, enlarged fractures, caves, conduit networks
- Karst in carbonate reservoirs:
 - impact reservoir storage capacity and subsurface fluid flow
 - collapse of wells
 - fluid loss during drilling
- Models need to incorporate these complexities

Localized flow - Conduits



Runkel, A. C. et al, (2003).

- 2ϕ 2K with enhanced permeabilities (Machado, 2020)
- Coupled 3D-1D Discrete Model (Murad; Pereira, 2020)
- Triple Porosity Models (Kang, 2004)
- EDKM (Correia et al, 2018)
 - Extension of the well established EDFM (Li and Lee, 2008; Moinfar et al. 2014)
 - Single porosity model with two grid domains (matrix and karst properties)
 - Communication between matrix/karst via special connections (NNC)
 - **Karst representation: same block size as refined geological grid**
 - **Transmissibility matrix/karst computed analytically.**

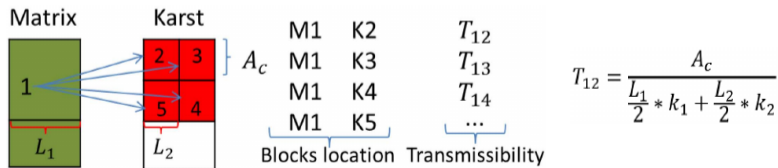
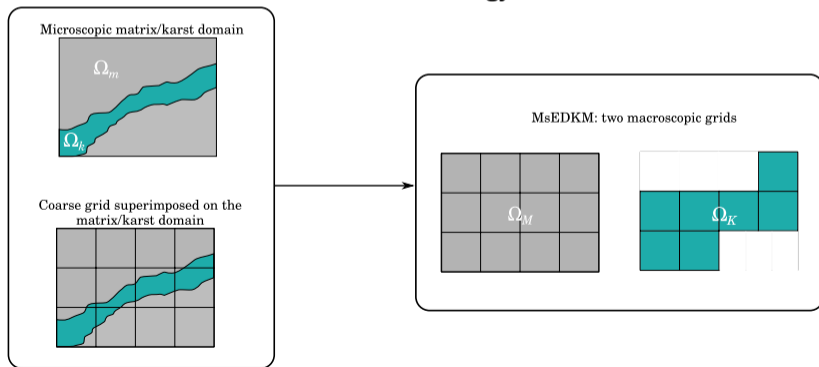
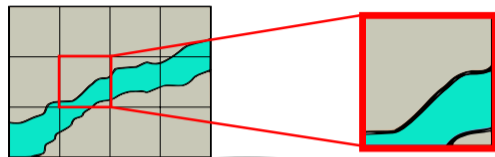
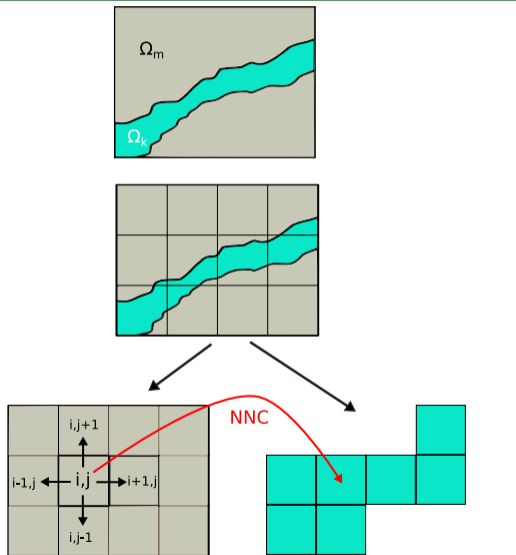


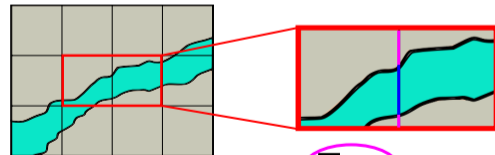
Figure 3—Application of special connections.

- MsEDKM: multiscale embedded discrete karst model
 - **Karst representation: same block size as the matrix grid**
 - **Matrix-karst transmissibilities computed via numerical simulations**
 - **Surrogate model trained on high-fidelity numerical simulations to reduce computational cost and enable scalable use of the methodology**





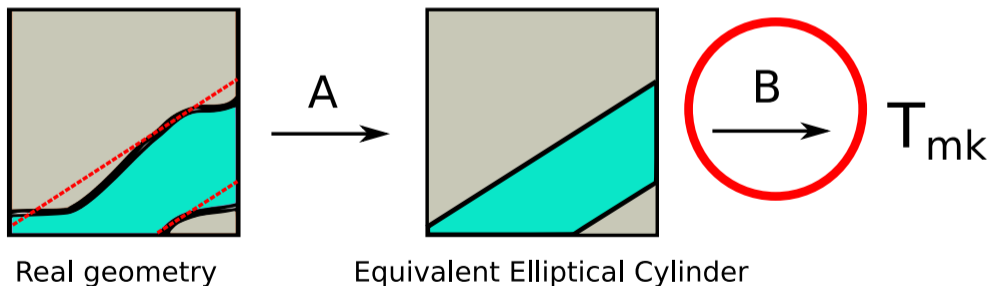
mass exchange between matrix and karst: T_{mk}



T_{mm}

T_{kk}

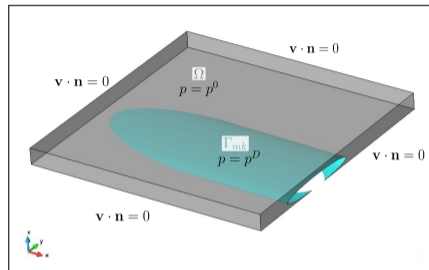
- **A.** Moment of inertia based upscaling (micro-meso)
Goal: regularization of the conduit surface roughness
- **B.** Flow based upscaling (meso-macro)
Goal: computation of hydraulic transmissibility between karst and matrix (T_{mk})



Numerical Computation of T_{mk} ($K_k \gg K_m$): No Geomechanical Effects

Solve the local microscopic transient problem:

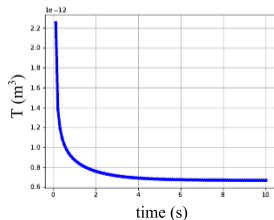
$$\left\{ \begin{array}{ll} \beta \frac{\partial p}{\partial t} + \nabla \cdot \mathbf{v} = 0 & \text{in } \Omega_m \\ \mathbf{v} = -\frac{\mathbf{K}}{\mu} \nabla p & \text{in } \Omega_m \\ p(\mathbf{x}, 0) = p^0(\mathbf{x}) & \text{in } \Omega_m \\ p(\mathbf{x}, t) = p^D(\mathbf{x}) & \text{on } \Gamma_{mk} \\ \mathbf{v} \cdot \mathbf{n} = 0 & \text{on } \Gamma_m \end{array} \right.$$



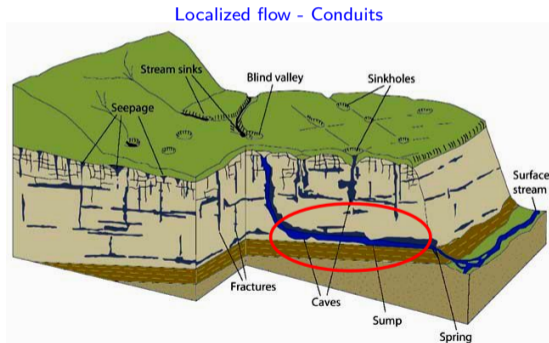
Compute T_{mk} :

$$T_{mk}(t) = \frac{\mu q}{\bar{p} - p^D}$$

$$T_{mk} = \lim_{t \rightarrow \infty} T_{mk}(t)$$



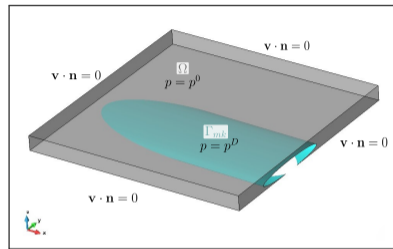
Extend the MsEDKM framework to account for geomechanical effects on flow through stress-dependent hydraulic properties.



Runkel, A. C. et al, (2003).

Solve the **non-linear** local microscopic transient problem:

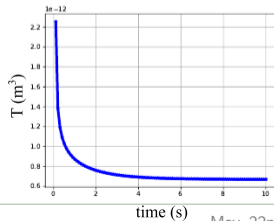
$$\left\{ \begin{array}{ll} \beta_{\text{eff}} \frac{\partial p}{\partial t} + \nabla \cdot \mathbf{v} = 0 & \text{in } \Omega_m \\ \mathbf{v} = -\frac{\mathbf{K}}{\mu} \nabla p & \text{in } \Omega_m \\ \mathbf{K} = \mathbf{K}(\phi(p)) & \\ p(\mathbf{x}, 0) = p^0(\mathbf{x}) & \in \Omega_m \\ p(\mathbf{x}, t) = p^D(\mathbf{x}) & \text{on } \Gamma_{mk} \\ \mathbf{v} \cdot \mathbf{n} = 0 & \text{on } \Gamma_m \end{array} \right.$$



Compute T_{mk} :

$$T_{mk}(t) = \frac{\mu q}{\bar{p} - p^D}$$

$$T_{mk} = \lim_{t \rightarrow \infty} T_{mk}(t)$$

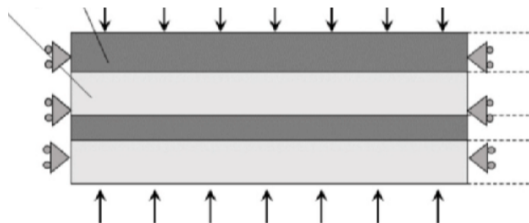


Analytical Geomechanics Approach: Oedometric Stress Path

Assumptions:

- *In-situ* state (input data): $\{p^{\text{ref}}, \sigma^{\text{ref}}, \mathbf{K}^{\text{ref}}, \phi^{\text{ref}}\}$.
- Total stress main directions are aligned to the coordinate system $\{x, y, z\}$
- **Prescribed total stress path (oedometric)**

- Lateral strains vanish on outer interface
 $\Delta\epsilon_x = 0$
- Constant vertical total stress $\Delta\sigma_V = 0$
- Effective stress changes with pressure
 - $\Delta\sigma'_V = \alpha\Delta p$
 - $\Delta\sigma'_H = \Delta\sigma'_h = \frac{\nu}{1-\nu}\Delta\sigma'_V$



$$\mathbf{K} = \mathbf{K}(p)$$

$$p \longrightarrow \Delta\sigma' \longrightarrow \varepsilon_v \longrightarrow \phi \longrightarrow \mathbf{K}$$

Mechanical response

Effective stress:

$$\sigma' = \sigma'^{\text{ref}} - \Delta\sigma',$$

with

$$\Delta\sigma' = \alpha (p - p^{\text{ref}}) \begin{pmatrix} \frac{\nu}{1-\nu} & 0 & 0 \\ 0 & \frac{\nu}{1-\nu} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Volumetric Strain:

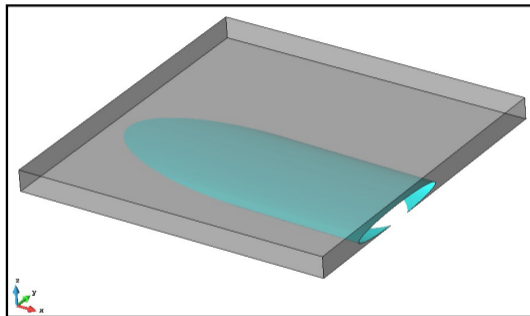
$$\varepsilon_v = \frac{\text{tr}(\Delta\sigma')}{3\mathbb{K}}$$

Porosity and permeability

$$\phi = 1 - (1 - \phi^{\text{ref}}) \exp(-\varepsilon_v)$$

$$\mathbf{K} = \mathbf{K}^{\text{ref}} \left(\frac{\phi}{\phi^{\text{ref}}} \right)^A$$

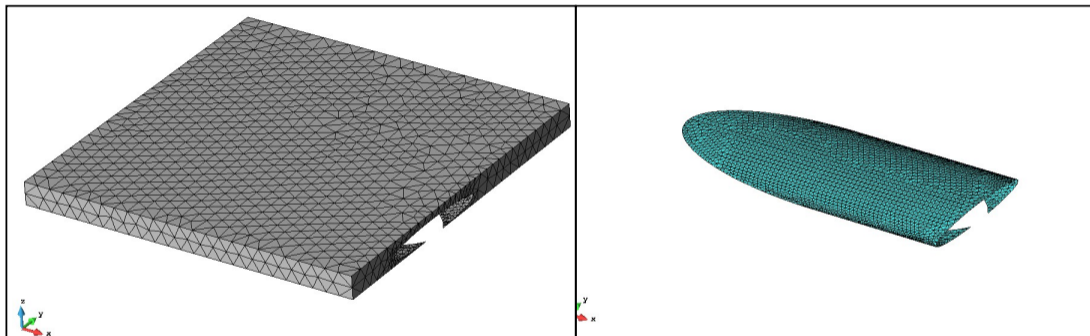
A : permeability-porosity sensitivity exponent.



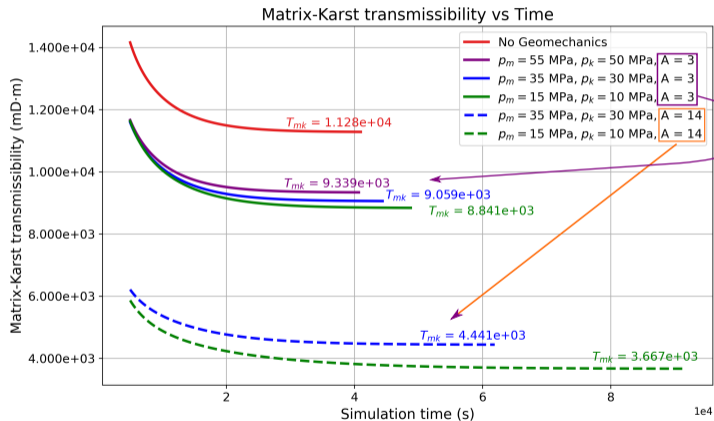
- cell dimension: 150x150x10 m
- conduit volume fraction: $\approx 10\%$

In-situ state:		
Parameter	Value	Unit (SI)
p^{ref}	60	MPa
σ^{ref}	(80, 80, 100)	MPa
\mathbf{K}^{ref}	(100, 100, 100)	mD
ϕ_{ref}	0.2	–

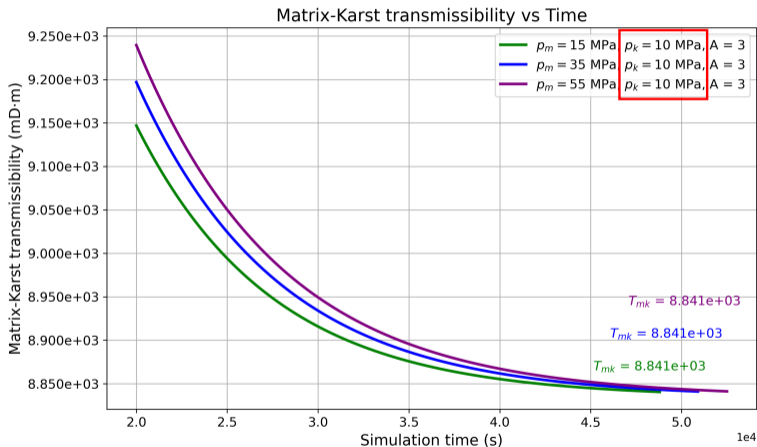
Input Parameters:		
Parameter	Value	Unit (SI)
E	2.2222×10^9	Pa
ν	0.3	–
\mathbb{K}_s	1.0×10^{32}	Pa
\mathbb{K}_f	2.0×10^9	Pa
α	1.0	–
μ_f	1.0×10^{-3}	Pa s
Δt	1.0×10^2	s



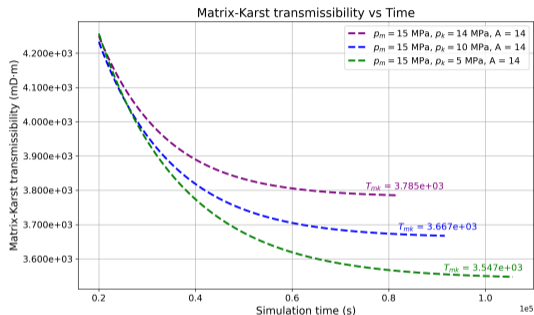
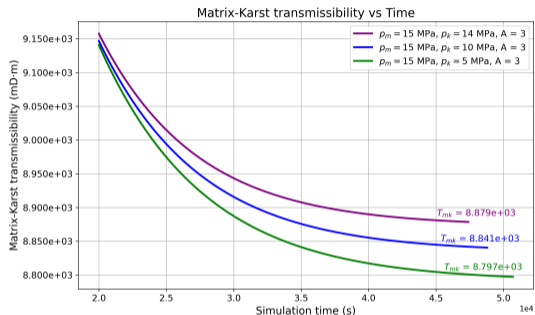
- Finer mesh along the conduit surface, where the flow rate is computed



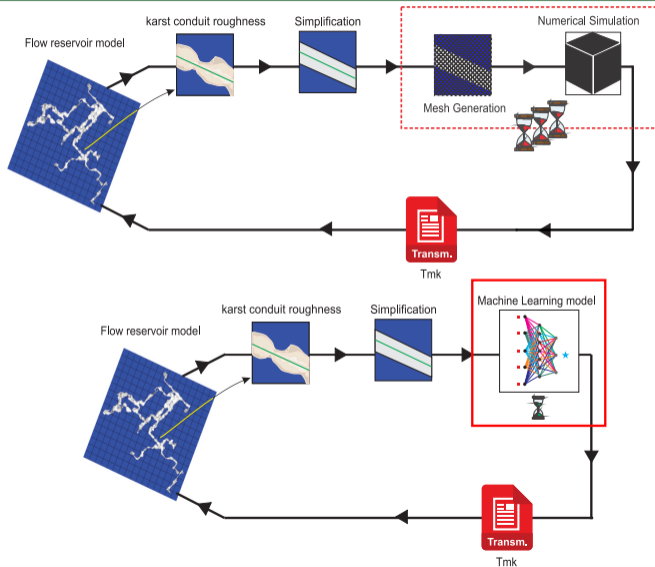
- $\Delta p = (p_m - p_k) = 5 \text{ MPa}$
- A : permeability-porosity sensitivity exponent
- Depletion scenario
- Geomechanical effects reduce transmissibility between matrix/karst transmissibility
- $A \uparrow, \phi \downarrow, \mathbf{K} \downarrow \Rightarrow T_{mk} \downarrow$
- Lower range of pressure: higher geomechanical impact



- Depletion scenario
- p_k fixed
- Geomechanical effects:
 $T_{mk} \downarrow$
- T_{mk} are the same for distinct p_m



- p_m fixed
- T_{mk} depends on p_k



Descriptor vector for the surrogate model

- Geometric and hydraulic attributes

$$\mathbf{X} = \{L_x, L_y, L_z, a_k, b_k, \mathbf{x}_k^{\text{in}}, \mathbf{x}_k^{\text{out}}, L_k, \eta_k, A_{mk}, V_k, \mathbf{K}\}$$

- Geomechanical attributes

$$\mathbf{X}_{\text{geomechanics}} = \{E, \nu, \mathbb{K}_s, \mathbb{K}_f, p^{\text{ref}}, \boldsymbol{\sigma}^{\text{ref}}, \mathbf{K}^{\text{ref}}, A, p_m, p_k\}$$

- Build a new database from hydromechanical numerical simulations
- Construct and train a surrogate model or predicting matrix-karst NNC transmissibilities
- Compute local transmissibilities accounting for geomechanical effects through permeability updates
- Implement the macroscopic flow model incorporating the surrogate model and the local transmissibilities

- MsEDKM: a systematic methodology for integrating karst conduits into reservoir simulators
- Ongoing work extends the MsEDKM framework to account for geomechanical effects through stress-dependent hydraulic properties
- Geomechanical effects are incorporated analytically, under a prescribed stress path, as an alternative to fully coupled hydromechanical numerical simulations
- Matrix–karst mass transfer is computed through numerical simulations, using flow-based upscaling
- ML-based surrogate model will enable large-scale simulations