GEOSCIENTIFIC MODEL DEVELOPMENT

Response to Community Comment CC1

PorousLab v1.1: a modular finite element framework for simulation of fractured porous media

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Giacomo Medici | CC1, 13 September 2026

Reviewer comments appear in shaded boxes. Author responses appear in dark blue; manuscript changes are listed separately. Addressed comments are labelled and struck through. Comment identifiers are added for navigation.

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CC1 Reviewer comment

Very good numerical solution on fluid flow in geological media. The research is also characterized by a good degree of novelty as a consequence of the interdisciplinary angle. You can follow my specific comments to improve the manuscript.

Author response

We thank you for your positive assessment of our work and for your suggestions to improve the manuscript. We address each of your specific comments below.

CC1.1 Reviewer comment

Lines 16–17. "CO_2 Storage, flow and transport". You can insert recent reviews that discuss all these topics:

- Baqer, Yousef, Xiaohui Chen. 2022. A review on reactive transport model and porosity evolution in the porous media." Environmental Science and Pollution Research 29(32), 47873–47901.
- Lupi, F., Agbotui, P. Y., Medici, G. 2026. Hydraulic Conductivity in the Mesozoic units of the Umbria-Marche succession (Italy); insights towards a sustainable management of carbonate aquifers worldwide. Sustainability, 18, 9297; https://doi.org/10.3390/su18189297.

Author response

The suggested reviews provide useful background on reactive transport and carbonate-aquifer hydraulics. This introductory paragraph is intended to illustrate application areas rather than provide a comprehensive review of each topic. It already includes references addressing CO_2 storage and flow in fractured porous media, which directly support the applications discussed. We therefore retain the existing references to keep the introduction focused on the numerical modeling context of this work.

CC1.2 Reviewer comment

Lines 67–80. When you discuss the link between fluid flow, and geomechanics, I suggest to be more explicit and conceptual. Which are the key aspects that PorePy and PorousLab incorporate? What about the relation between fracture aperture and orientation of the stress tensor in the sub-surface?

Author response

The coupling between geomechanics and fluid flow in `PorousLab` follows the standard hydro-mechanical formulation described in Section 3. Mechanical equilibrium is governed by the linear momentum balance, with pore pressure entering through Biot's effective-stress decomposition (Eq. (5)). Conversely, mechanical deformation contributes to the fluid mass balance through the volumetric strain rate (Eq. (19)). The strong form of the governing

problem is therefore standard. The embedded finite element method (E-FEM) provides the numerical treatment of discontinuities within this coupled problem. PorePy also represents coupled flow and deformation in fractured porous media, with its formulation described by Keilegavlen et al. (2021).

For an embedded discontinuity, the displacement jump and cohesive tractions are expressed in the local coordinate system defined by its normal and tangential directions. The constitutive relationship $\mathbf{t}_\mathrm{d} = \mathbf{t}_\mathrm{d}(\mathbf{u}_\mathrm{d})$, defined immediately after Eq. (42), relates the cohesive tractions to the displacement jump, while Eq. (42) enforces equilibrium with the stresses in the surrounding continuum. The orientation of the discontinuity relative to the stress field therefore affects the resolved normal and shear tractions and, through the constitutive relationship, the resulting displacement jump.

When a coupled hydro-mechanical analysis is adopted, the fracture aperture is updated from the normal component of this displacement jump. The aperture then determines the longitudinal permeability through Eq. (46), producing the cubic dependence of hydraulic conductance on aperture. Thus, the stress state, fracture orientation, fluid pressure and constitutive properties jointly govern fracture opening and its effect on flow.

CC1.3 Reviewer comment

Lines 67–80. Improve the conceptual description of the novelty of PorousLab.

Author response

We have revised the contribution paragraph in Section 1 to clarify the novelty of `PorousLab`. The revised text is reproduced below.

Changes in the manuscript

Section 1, contribution paragraph: We have revised the contribution paragraph to identify the integrated capabilities and explain their role in formulation development and verification.

> This paper presents `PorousLab`, an open-source, object-oriented finite-element framework implemented in MATLAB for computational geomechanics researchers developing, verifying, and prototyping porous-media formulations. Its contribution is the integration of coupled flow and deformation, nonlinear bulk constitutive models, continuation procedures for quasi-static mechanical analysis, and embedded-discontinuity formulations within a common software architecture. The architecture separates model definition, material behavior, element formulations, and solution procedures. This organization supports the development and assessment of individual formulations while reusing model-construction, assembly, and post-processing components. The resulting scripted workflow connects formulation development with numerical verification within the same computational environment.

CC1.4 Reviewer comment

Lines 67–80. Is PorousLab capable to represent exchanges matrix-fractures? Not clear in the introduction.

Author response

`PorousLab` represents matrix–fracture fluid exchange in its saturated single-phase hydraulic and hydro-mechanical formulations. We have added a sentence to the Introduction to make this capability explicit. We have also revised Section 3.7.3, "Fluid flow inside the discontinuity," to explain the pressure-driven leak-off across each fracture face and how it enters the matrix and fracture balance equations. The relevant revised passages are reproduced below.

Changes in the manuscript

1. **Section 1, capabilities paragraph:** We have added the following sentence immediately after the sentence ending "conform to their geometry."

   > For single-phase flow, the embedded formulations represent flow along fractures and fluid exchange with the surrounding porous matrix.

2. **Section 3.7.3, "Fluid flow inside the discontinuity":** We have clarified the representation of matrix–fracture fluid exchange in the passage introducing the leak-off law and explaining its contribution to the matrix and fracture balance equations.

   > Fluid exchange between the discontinuity and the surrounding porous matrix is described by the leak-off law (Segura and Carol, 2004)
   >
   > $$q_{\mathrm{d,l}}^{t\pm} = \lambda_{\mathrm{d}}^{\pm}\left(p_{\mathrm{d,l}} - p_{\mathrm{l}}^{\pm}\right), \qquad q_{\mathrm{d,l}}^{t} = q_{\mathrm{d,l}}^{t+} + q_{\mathrm{d,l}}^{t-}, \tag{R1}$$
   >
   > where $p_{\mathrm{l}}^{\pm}$ are the matrix pressures on the fracture faces, and $\lambda_{\mathrm{d}}^{\pm}$ are the leak-off coefficients. Each face flux is positive from the discontinuity towards the porous matrix. The total leak-off represents the net outflow from the discontinuity. At each face, fluid leaving the discontinuity enters the adjacent porous matrix, so the same flux appears with opposite signs in their balance equations.

CC1.5 Reviewer comment

Line 105. Describe the specific objectives of your research by using numbers (e.g., i, ii, and iii) at the end of the introduction.

Author response

The objectives are stated in the concluding part of the introduction: to present `PorousLab` and its modeling capabilities, describe the numerical formulations and software architecture, and verify the implemented formulations through comparisons with reference solutions. We have retained their presentation in prose to keep these objectives connected to the discussion of the framework's contribution and intended use.

CC1.6 Reviewer comment

Lines 614–634. Highlight novelty of the research in the conclusion.

Author response

We have revised the opening paragraph of the Conclusions to clarify that `PorousLab`'s novelty lies in integrating the implemented formulations and analysis procedures within a common MATLAB architecture for formulation development and verification. The revised text is reproduced below.

Changes in the manuscript

Conclusions, opening paragraph: We have replaced the sentences beginning "The contribution of the framework" and "In this sense" to make the software contribution and its research purpose explicit.

> This work presented `PorousLab`, an open-source, object-oriented finite-element framework implemented in MATLAB for the simulation of porous-media problems involving coupled hydromechanical formulations with two-phase flow. The novelty of this work lies in integrating coupled flow and deformation, nonlinear bulk constitutive models, continuation procedures for quasi-static mechanical analysis, and embedded-discontinuity formulations within a common MATLAB software architecture. This integration supports the development and assessment of individual formulations while reusing model-construction, assembly, and post-processing components.

CC1.7 Reviewer comment

Table 1. Are those numerical solutions for fluid flow? This is unclear from the caption. The information in the brackets is not sufficient to explain the content of the table.

Author response

Table 1 compares representative open-source software frameworks for numerical modeling of geological media. Its scope extends beyond fluid flow: the "Physics" column identifies the mechanical (M), hydraulic (H), thermal (T), and chemical (C) processes supported by each framework. The other columns summarize their implementation and modeling capabilities. The purpose of the table is to place `PorousLab` within the context of existing multiphysics frameworks. We have revised the caption and accompanying text to clarify the scope of Table 1 and explain the information presented in each column.

Changes in the manuscript

1. **Table 1 caption:** We have revised the caption to read as follows.

   > Representative open-source frameworks for multiphysics modeling of geological systems.

2. **Section 1, paragraph beginning "The table summarizes":** We have expanded this paragraph to explain the table columns and the abbreviations used.

   > The table summarizes the development platform, supported thermal (T), hydraulic (H), mechanical (M), and chemical (C) processes, multiphase-flow capabilities, bulk constitutive behavior, and main spatial discretization families. Platform identifies the principal implementation languages and available Python interfaces or tools. "Yes" and "No" indicate whether multiphase flow is supported in the versions considered. A dash in the Bulk behavior column denotes a capability not represented in the entry. "General" denotes bulk constitutive behavior beyond linear elasticity, such as plasticity or damage; this classification excludes fracture-contact laws. VEM and MFD denote the virtual element and mimetic finite difference methods, respectively.

CC1.8 Reviewer comment

Figure 1. Do you need an approximate spatial scale?

Author response

Figure 1 is a schematic representation of the solid, liquid and gas phases within a representative elementary volume. It does not depict a specific material or a measured pore geometry, so assigning a numerical spatial scale would not be appropriate. Its purpose is to illustrate the phase composition considered in the continuum formulation.

CC1.9 Reviewer comment

Figure 2. What do you mean by "strong discontinuity"? Please, improve the caption.

Author response

Strong discontinuity is standard terminology in the literature on numerical modeling of fractures, cracks, and faults. We have added a definition of "strong discontinuity" at the beginning of Section 3.7.1 to clarify that a primary field can exhibit a finite jump across the discontinuity surface.

Changes in the manuscript

Section 3.7.1, "Strong Discontinuity Approach": We have replaced the opening sentence with the following text.

> Fractures and faults are modeled as strong discontinuities, across which primary fields such as displacement or pore pressure may exhibit finite jumps. The formulation is based on the Strong Discontinuity Approach and implemented through the Embedded Finite Element Method (E-FEM) (Cavalcanti et al., 2024a, b).

CC1.10 Reviewer comment

Figure 6. Make the figure larger and improve the graphic resolution.

Author response

Figure 6 is provided in vector format, so its lines and mathematical labels are not limited by raster resolution and can be magnified in the PDF without loss of sharpness. Increasing the export resolution would therefore not improve its graphical quality. The two panels are arranged side by side to facilitate comparison between the local and nodal discretizations of the enriched displacement field.

CC1.11 Reviewer comment

Algorithm 1. The use of bold is unclear.

Author response

Bold text identifies the four main stages of the simulation workflow, while indented entries describe the configuration tasks. We now clarify this visual hierarchy in the paragraph introducing Algorithm 1.

Changes in the manuscript

Section 5, paragraph introducing Algorithm 1: We have added an explanation of the bold text and indented entries after the opening sentence. The revised opening reads:

> Algorithm 1 summarizes the main steps required to define and execute a simulation. Bold text identifies the four main workflow stages, while indented entries describe the tasks within the model and analysis configuration stages.

CC1.12 Reviewer comment

Figure 15. The boundary conditions are not clear. Do you need adding labels or a legend?

Author response

The boundary-condition symbols in Figure 15 follow standard conventions in solid mechanics. The roller supports indicate zero normal displacement: $u_x = 0$ along the lateral boundaries and $u_y = 0$ along the bottom boundary. The red arrows represent a uniform compressive traction of 70 MPa applied to the top boundary.

The labels P_0 and $P_0 + \Delta P$ indicate the prescribed pore-pressure values in the surrounding layers and the pressurized reservoir, respectively. As described in Section 6.2, $P_0 = 35$ MPa and $\Delta P = 20$ MPa. These labels describe the pore-pressure field prescribed within the domain, rather than hydraulic boundary conditions. The figure complements the description of the loading procedure provided in the text.