Thermo-Mechanical Subsurface Energy Storage

Final report – NFR project 250223

Senior project members: Professors Jan Martin Nordbotten (lead), Inga Berre, Martin Fernø, Florin Radu; Assoc. Prof. Kundan Kumar; Researcher Eirik Keilegavlen

PhD students graduated: Mats K. Brun, Ana Budisa, Runar Lie Berge, Ingeborg Gjerde.

Early career researchers: Elyes Ahmed, Jakub Both, Omar Duran, Michele Starnoni, Ivar Stefansson

Executive summary

The primary goal of the project has been to *establish the mathematical models and numerical methods required to assess and develop subsurface energy storage.* The project has achieved substantial progress towards this goal, focusing on the four subareas: (i) modeling fracture networks as mixed dimensional geometries with low dimensionality gap; (ii) modeling wells as mixed-dimensional geometries with high dimensionality gap; (iii) coupled multi-process-structure interaction combining the previous two subareas; (iv) Accurate, robust and efficient discretization methods and solvers. Targeting complex processes as well as complex geometries, the key results involve a holistic treatment of coupled thermo-hydro-mechanical (THM) models from derivation to analysis to numerical solution; the development of mature numerical modeling capabilities of fluid-saturated fractured porous media under friction and contact conditions; a detailed mathematical and numerical understanding of 1D-3D coupled fluid flow; and the development and analysis of problem-tailored numerical solver technology.

The key deliverables have been documented through four PhD theses, as well as publications in high-level peer-reviews journals. Additionally, the novel open-source in-house research code PorePy has been developed, which offers capabilities to simulate coupled THM processes in fractured porous media[17]. A comprehensive list of discretization methods has been implemented as well as a flexible infrastructure to combine them. The tool offers tutorials, has successfully participated in collaborative benchmark studies, and is also used and developed outside the research group in Bergen. Further development is part of ongoing work that will eventually lead to new advanced numerical modeling and methods for projects related to coupled process-structure interaction in the subsurface.

The TheMSES project has provided extensive knowledge and novel research results motivated by the coupling of complex processes interacting with complex structures. The research conducted has also other applications than subsurface energy storage as enhanced geothermal systems and CO2 storage. The project has also raised new research questions, leading to recently awarded projects to the research group.

A popular science summary of the project results and PhD thesis in the project are compiled in a series of five short films available on the project webpage (https://www.uib.no/en/rg/pmg/150651/themses-final-results-and-impacts).

Research results

A summary of results from each work package, including selected publications, is given in the following.

WP1: Fracture development in cyclically stressed porous materials

Goal: to Identify dominating effects in the development of hydraulic properties of the storage reservoir during successive operation cycles.

Significant progress has been made to examine the numerical modeling of the mechanical behavior of fractured porous media with focus on slip and frictional contact of existing fractures[1,2], as well as fracture propagation[3,4]. A fully coupled, general model for flow in deformable, fractured media has been developed, allowing for simulating the complex process-structure interaction and resulting slip and reactivation of existing fractures in subsurface reservoirs. By this, hydraulic changes of the reservoir, resulting from external changes in the operating conditions of an energy storage site, can be quantified. A tight coupling between the interacting features has been found by numerical investigations. Moreover, fracture propagation has been modeled using a widely-used, flexible phase-field approach, whose numerical solution however is often computationally expensive. Stabilized linearization techniques and acceleration strategies developed in this WP, allow for a significant reduction of computational cost, making the modeling approach more feasible and valuable when considering large-scale domains.

Moreover, extensive advances have been made in numerical method development for the accurate approximation of coupled processes on complex geometries[9,10]. A unified framework for flow in fractured porous media has been established. Based on Mortar techniques, it allows for flexibly combining a variety of different discretization methods on non-conforming meshes, tailored to features present in a realistic geological reservoir. Utilizing similar concepts, a stable finite volume discretization has been developed for fractured poroelastic media under frictional contact conditions. These discretization techniques provide the basis for implementation in the software package PorePy, a major contribution of WP4.

WP2: Upscaling and discretization of coupled geomechanics, flow and geochemistry

Goal: to derive and numerically solve an upscaled mathematical model for coupled geomechanics/flow/chemistry under non-isothermal conditions accounting for pore clogging and structure damage.

Several key results have been established leading to better understanding the direct coupling of deformation of, and flow in, porous media under non-isothermal conditions[5,6,7], also called thermo-poroelasticity. An upscaled model has been derived using the theory of asymptotic homogenization, resulting in a non-linear extension of the quasi-static Biot equations including non-linear convection. Its well-posedness has been rigorously established under assumptions met in practical applications.

A robust finite volume discretization, based on previous works on poroelasticity[8], has been provided for thermo-poroelasticity, satisfying local mass and momentum balance; thereby, coupled flow and deformations under non-isothermal conditions can be effectively simulated by finite volume software frameworks supporting multi-point flux approximations. Finally, numerical solution techniques have been proposed for the non-linear multi-physics model for thermo-poroelasticity, based on a sequential solution of stabilized single-physics problems. After all, the provided numerical framework allows for an efficient and robust approximation of thermo-poroelasticity.

WP3: Non-equilibrium alternating-direction flows in porous media

Goal: to mathematically analyze and numerically discretize non-standard flow models.

The main challenge of alternating flow directions occurs near wells when these are operated as alternatingly injectors and producers. In WP3, a deeper mathematical and numerical understanding of near-well fluid flow was established by developing the theory of mixed-dimensional geometries with high dimensionality gap[11,12]. Via a careful theoretical well-posedness analysis of elliptic problems with line sources, the correct singular behavior of the solution to 1D-3D coupled flow in porous media has been identified. Exploiting this knowledge, an accurate, yet cheap, singularity removal method, based on the finite element method, is provided for the discretization with optimal a priori error estimates. Finally, the results allow for accurate simulation of arbitrary one-dimensional networks embedded in a 3D medium.

Further relevant non-standard physical phenomena include a hysteretical and dynamical capillary pressure formulation in the context of multiple fluid phases. Related to this WP, numerical solver technology involving efficient linearization, iterative coupling and acceleration has been developed to confront the arising highly non-linear mathematical models[20].

WP4: Integrated solvers, software and knowledge development

Goal: to develop numerical solvers implemented in an open-source software framework addressing the established mathematical models.

Extensive development has been conducted in the development of iterative solvers tailored to linear and non-linear multi-physics models for coupled processes in porous media[13,14,15]. Fixed-point iteration schemes are developed, exploiting the inherent block-structure and merely sequentially solving the different subproblems. Robustness and convergence are achieved via stabilization techniques. Separately, tailored preconditioners for Krylov subspace methods are developed for the mixed-dimensional discretization of flow in fractured porous media[16,17]. The resulting preconditioners are robust with regard to discretization and physical parameters.

To exploit synergies between the different work packages, the open-source framework PorePy has been developed[18,19]. It is based on the flexible, mixed-dimensional discretization framework, developed in WP2, as well as numerical solvers, for flow in fractured poroelastic media under non-isothermal and frictional contact conditions, as developed in WP1. The code and scripts for all publications involving PorePy simulations are publicly available on github, enabling reproducability of all results.

Project implementation and resource use

The project has been to most extent implemented according to the proposed plan. The project has funded recruitment positions for Elyes Ahmed (postdoc, UiB), Runar Berge (PhD, UiB), Mats Brun (PhD, UiB), Ana Budiša (PhD, UiB), Ingeborg Gjerde (PhD, UiB), Michele Starnoni (postdoc, UiB).

Due to earlier resignation of Elyes Ahmed (moved to SINTEF) and Michele Starnoni (moved to Politecnico di Turino) leaving for researcher positions, researchers Jakub Both, Omar Duran and Ivar Stafansson have been additionally funded in the final stage of the project. Furthermore, due to the Covid-19 pandemic, originally planned resources for international travels as well as for the organization of a final conference could not be utilized before the end of the project. These funds we partially used to make a series of five videos giving insight into the project results.

Impact

During the TheMSES project period, the research group has significantly raised its national and international profile. Four key milestones in this regard are

1. The VISTA funded Center for Complex Subsurface Dynamics (2021-2026; directed by Berre)
2. The NFR petrocenter CSSR (2022-2030; center deputy directors Nordbotten and Fernø)
3. The trust of organizing major international conferences
    a. ENuMath 2017 (chaired by Radu)
    b. SIAM Geosciences conference 2023 (chaired by Nordbotten);
4. The award of an ERC Consolidator Grant for Berre

The scientific impact of the project has been significant, as has been reflected in the invitations and citations related to the TheMSES work and publications, including plenary talks at major international conferences. Furthermore, in addition to the major funding mentioned above, several smaller complementary projects building on the results of TheMSES have been proposed and awarded.

The open-source in-house simulation tool PorePy has been built up from ground during the project. PorePy provides an approach to rapid prototyping for simulating coupled processes in complex geometries. It provides a flexible framework for modeling THM processes including frictional contact on hierarchical geometric structures with low dimensionality gap, coupling arbitrary domains with fractures and intersection of fractures. PorePy is under constant development and will be the basis for future and ongoing projects and external collaborations. In fact, PorePy is also used and in part developed by external partners at the Politecnico di Milano (Italy) and Politecnico di Turino (Italy). Furthermore, it has taken part in an international benchmark study.

Dissemination and exploitation of results

Results have been published in 35 high-level peer-reviewed journals and in conference proceedings papers. The project team has given more than 50 talks at international research conferences, including several plenary talks. Popular science dissemination has also been undertaken through various channels. The complete list of results is available on NFR webpages (https://prosjektbanken.forskningsradet.no/project/FORISS/250223).

Publications mentioned in this report

1 Berge RL, Berre I, Keilegavlen E. Reactivation of Fractures in Subsurface Reservoirs—A Numerical Approach Using a Static-Dynamic Friction Model. In EnuMATH proceedings, 2017 Sep 25 (pp. 653-660). Springer, Cham.

2 Berge RL, Berre I, Keilegavlen E, Nordbotten JM, Wohlmuth B. Finite volume discretization for poroelastic media with fractures modeled by contact mechanics. Int. J. for Numerical Methods in Eng. 2020 Feb 28;121(4):644-63.

3 Brun MK, Wick T, Berre I, Nordbotten JM, Radu FA. An iterative staggered scheme for phase field brittle fracture propagation with stabilizing parameters. Comp. Meth. in Applied Mechanics and Eng. 2020 Apr 1;361:112752.

4 Storvik E, Both JW, Sargado JM, Nordbotten JM, Radu FA. An accelerated staggered scheme for phase-field modeling of brittle fracture. Computer Meth. in Applied Mechanics and Engineering. 2021 Aug 1; 381, 113822.

5 Brun MK, Berre I, Nordbotten JM, Radu FA. Upscaling of the coupling of hydromechanical and thermal processes in a quasi-static poroelastic medium. Transport in Porous Media. 2018 Aug 1;124(1):137-58.

6 Brun MK, Ahmed E, Nordbotten JM, Radu FA. Wellposedness of the fully coupled quasi-static thermo-poroelastic equations with non-linear convective transport. J. of Math. Analysis and Appl. 2019 Mar 1;471(1-2):239-66.

7 Nordbotten JM, Keilegavlen E. An introduction to multi-point flux (MPFA) and stress (MPSA) finite volume methods for thermo-poroelasticity. In Polyhedral Methods in Geosciences. Springer, Cham., 119-158, 2021.

8 Nordbotten JM. Cell-centered finite volume discretizations for deformable porous media. International journal for numerical methods in engineering, 100(6), 399-418, 2014.

9 Berge RL, Berre I, Keilegavlen E, Nordbotten JM, Wohlmuth B. Finite volume discretization for poroelastic media with fractures modeled by contact mechanics. Int. J. for Numerical Meth. in Eng.. 2020 Feb 28;121(4):644-63.

10 Nordbotten JM, Boon WM, Fumagalli A, Keilegavlen E. Unified approach to discretization of flow in fractured porous media. Comput Geosciences. 23, 225–237, 2019.

11 Gjerde IG, Kumar K, Nordbotten JM. A singularity removal method for coupled 1D–3D flow models. Computational Geosciences. 2020 Apr;24(2):443-57.

12 Gjerde IG, Kumar K, Nordbotten JM, Wohlmuth B. Splitting method for elliptic equations with line sources. ESAIM: Mathematical Modelling and Numerical Analysis. 2019 Sep 1;53(5):1715-39.

13 Brun MK, Wick T, Berre I, Nordbotten JM, Radu FA. An iterative staggered scheme for phase field brittle fracture propagation with stabilizing parameters. Comp. Meth. in Applied Mechanics and Eng. 2020 Apr 1;361:112752.

14 Ahmed, E., Nordbotten, J. M., & Radu, F. A. (2020). Adaptive asynchronous time-stepping, stopping criteria, and a posteriori error estimates for fixed-stress iterative schemes for coupled poromechanics problems. Journal of Computational and Applied Mathematics, 364, 112312.

15 Ahmed, E., Fumagalli, A., Budisa, A., et al., Robust Linear Domain Decomposition Schemes for Reduced Nonlinear Fracture Flow Models. SIAM J. on Numerical Analysis. 59(1), 583–612., 2021.

16 Budiša A, Hu X. Block preconditioners for mixed-dimensional discretization of flow in fractured porous media. Computational Geosciences. 2020 Jul 4:1-6.

17 Budisa A, Boon WM, Hu X. Mixed-dimensional auxiliary space preconditioners. SIAM Journal on Scientific Computing. 2020;42(5):A3367-96.

18 Keilegavlen, Eirik, et al. "PorePy: an open-source software for simulation of multiphysics processes in fractured porous media." Computational Geosciences (2020): 1-23.

19 https://github.com/pmgbergen/porepy

20 Illiano, D., Both, J.W., Pop, I.S. and Radu, F.A., (2020). Efficient Solvers for Nonstandard Models for Flow and Transport in Unsaturated Porous Media. arXiv preprint: arXiv:2012.14773.