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EMOD

Engineering models for hydro-shearing stimulation

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Zusammenfassung

Résumé

Le projet EMOD a permis le développement d'un solveur numérique basé pour la simulation des opérations de stimulation par hydro-shearing en géothermie, en 2D et 3D. La compréhension de la propagation des ruptures frictionnelles induites par l'injection de fluide a considérablement progressé au cours du projet, notamment grâce au développement de nouvelles solutions analytiques. Ces solutions ont en particulier permis de vérifier le simulateur numérique entièrement couplé qui a été développé. En ce sens, ce simulateur peut être considéré comme étant à la pointe de la technologie. Ses fonctionnalités permettent d'examiner en détail un certain nombre de problèmes liés à la stimulation hydraulique (notamment l'importance de la croissance des fractures après l'arrêt de l'injection et la microsismicité associée). Le modèle numérique a également été utilisé pour reproduire des stimulations hydrauliques réalisées sur le terrain (Bâle 2006, Utah Forge 2022, Soultz-sous-Forêts 1993, Rittershoffen 2013). Il peut reproduire à la fois les observations microsismiques et les mesures de pression. Le modèle numérique contient les principales fonctionnalités nécessaires pour concevoir les opérations de stimulation hydraulique en pratique et évaluer l'étendue de la perturbation des contraintes. Il est donc utile pour réduire les risques liés à la stimulation hydraulique pour un site et une séquence d'injection donnés.

Summary

The EMOD project has allowed the development of a physics based numerical solver for the simulation of hydro-shearing stimulation operations in geothermal energy in both 2D and 3D. The understanding of the propagation of fluid-driven frictional ruptures has significantly advanced during the project, notably thanks to the development of novel analytical solutions. These solutions have in particular allowed to verify the fully-coupled numerical simulator developed. As such, this simulator can be considered as state of the art. Its features allow to investigate in details a number of issues associated with hydraulic stimulation (notably the importance of post shut-in fracture growth and the associated micro-seismicity). The numerical model has also been used to reproduced hydraulic stimulation performed in the field (Basel 2006, Utah Forge 2022, Soultz-sous-Forêts 1993, Rittershoffen 2013). It can reproduce both micro-seismic and pressure observations. The numerical model contains the main features required to design hydraulic stimulation in practice and assess the extent of the stress perturbation. It is thus useful to de-risk hydraulic stimulation for a given site and planned injection sequence.

Contents

Abbreviations

EMOD: Engineering MODels for hydraulic stimulation

1 Introduction

1.1 Background information and current situation

There is currently a lack of engineering models and workflow to design and optimize hydraulic stimulation of deep geothermal reservoirs in 3D – even more so in the multi-stage context put forward for the Haute-Sorne project by Geo-Energie Suisse. In comparison, hydraulic fracturing jobs in the oil and gas industry are routinely designed using advanced numerical models to simulate the propagation of fractures during injection operations. These models are usually first calibrated during smaller scale operations - so-called data-frac. Unfortunately, the theory and accompanying models for tensile / opening mode hydraulic fracturing do not apply to the case of hydro-shearing stimulation (and a combination of both), and as such these existing software cannot be used to design hydro-shearing stimulations.

1.2 Purpose of the project

It is clear that the engineering of hydro-shearing stimulation needs to advance further in order to lower cost and increase efficiency as well as safety – to unlock deep geothermal resources in an efficient and sustainable manner. In order to do so, a sound hydromechanical model must be developed in a similar way than the theory of linear hydraulic fracture mechanics. In addition, the developed theory and associated numerical solvers must be confronted to the existing dataset of large-scale hydraulic stimulation performed during past as well as ongoing geothermal projects.

1.3 Objectives

This project builds upon the achievement of the StimDesign project (SFOE SI/501354-01) with the aims to i) complete the extension to three-dimensions of the modeling framework developed during the StimDesign project, ii) develop a series of semi-analytical solutions allowing to test the accuracy and robustness of numerical models, iii) couple the 3D hydro-shearing model to a simplified well flow model (to be able to compare predictions with observables like pressure and rate measured in the well) and iv) develop a robust solver for the simulation of multiple sequential injections from a deep wellbore. Furthermore, the project will also revisit past hydraulic stimulations performed during previous geothermal developments (Basel, Soult-sous-Forêts, Rittershoffen, Utah Forge) to test its. Notably, we aim to demonstrate that the developed theory and model can reproduce the well pressure and micro-seismicity migration measured during past injections.

This is an important step toward the further use of physics-based model to define injection requirements and optimize stimulation operations.

2 Procedures and methodology

2.1 Model assumptions

The model assumes a linearly elastic isotropic medium containing a set of pre-existing discontinuities (fractures). The hydro-mechanical behaviour of these pre-existing fractures are modelled as zero-thickness poro-elasto-plastic interfaces. Such a formalism allows to simulate a large variety of behaviour observed: notably irreversible frictional behaviour, cohesion (if present), non-linear elastic closure and opening etc. We have particularly focused on the case of a frictional interface with a non-associated flow rule (dilatancy) and a linear elastic behaviour. Fluid flow in the pre-existing fractures is modelled via the classical width integrated version of Darcy flow which is in its form similar to the well-known lubrication approximation which results from the averaging across the fracture width of the balance of fluid mass and momentum. This formalism automatically accounts for fracture deformation and fluid/gouge material compressibility. In addition, different constitutive models for the evolution of both the frictional behaviour of the interface and its permeability can be used. We have notably implemented the case of a constant permeability, and a modified version of the classical cubic law which relates permeability changes non-linearly to the variation of interface aperture/closure (accounting for an initial hydraulic transmissibility).

In addition, the theoretical formalism and code architecture developed, allows one to implement different type of constitutive hydro-mechanical behaviour for both the mechanical and flow behaviours of the fractures.

This numerical solver recognizes the intrinsic non-linear nature of the hydro-mechanical couplings, the fact that deformation impacts fluid-flow non-linearly and vice-versa. It is grounded in the first principle of continuum mechanics. We have also developed the most in-depth suite of verification tests for the modelling of fluid-driven ruptures, thus ensuring code accuracy and robustness under widely different injection conditions.

A brief summary description is included in 3.3 for clarity. The complete detailed formulation of the model, its assumptions as well as and its numerical implementation is presented in details in the technical appendix A to this report.

2.2 Inputs and outputs

Before briefly discussing the numerical algorithm implemented, we list below the inputs and outputs of this model. These are important information for end-users.

Inputs:

- In-situ stress (tensor) and pore-pressure (scalar) fields (prior to the beginning of the simulated injection). These can be either uniform or spatially varying.
- Geometry of the pre-existing fractures. The fracture(s) can be planar or non-planar – discretized in segments (2D) or via triangular elements (3D).
- Elastic properties of the rock matrix (uniform): e.g. Young's modulus and Poisson's ratio.
- Fluid properties: viscosity and compressibility
- Constitutive parameters of the fracture(s):
    - Shear and normal stiffness (Pa/m), the possible non-linear hyperbolic dependence of the normal stiffness (Barton-Bandis hyperbolic model)
    - Frictional properties: for the constant friction model: a friction and dilatancy coefficient, for the slip-weakening model: peak friction and dilatancy coefficients, residual friction coefficient and critical slip distance.
    - Cohesion and tensile strength of the fracture (if any) and an opening critical distance over which cohesion and tensile strength vanishes.
- Flow properties
    - For the constant permeability case: interface permeability, interface storage coefficient
    - For the cubic law model: initial hydraulic aperture or initial hydraulic transmissibility, initial interface storage coefficient.
- Injection parameters:
    - Location of the injection point – either injection rate history or injection pressure history.

- Wellbore storage coefficient

Outputs:

- At every time-steps, the algorithm obtains:
- The fluid pressure and displacement discontinuities (normal and shear components) in **all the elements** discretizing the pre-existing fractures.
- The elastic and plastic components of the displacement discontinuities (normal and shear).
- The rate of both displacement discontinuities (normal and shear) and fluid pressure.
- The current effective tractions (normal and shear) at all collocation points of the mesh
- The value of the plastic yield function F at all collocation points of the mesh, which allow to track the evolution of the extent of the rupture area on the pre-existing fracture(s).
- The current values of the interface permeability at all elements (in the case of non-linear permeability laws) can also be output, or any other hydraulic properties (transmissivity etc.).
- Statistics on solver convergence (norm of residuals, number of iterations etc.)

The current stresses in the surrounding matrix (at given points) can be computed via an additional post-processing step if needed by running a boundary element module.

2.3 Numerical algorithm

We use an implicit time-stepping algorithm which solves in a fully coupled manner: i) the overall elasto-static equilibrium of the medium, ii) the local elasto-plastic like constitutive relation for the behavior of the pre-existing fractures and iii) the fluid flow evolution (including the effect of permeability as well as aperture changes). We solve the elastic equilibrium of the overall fractured medium via a collocation boundary element method. The elastic solver assumes quasi-static deformation although a quasi-dynamic approximation can be easily added. Different order of interpolation for the displacement discontinuities are available in our boundary element code – either piece-wise constant (low order element) or quadratic interpolation. In such a collocation boundary element scheme, the boundary integral equations relating tractions to displacement discontinuities on the fracture plane are enforced at a set of collocation points inside the element – and no continuity is enforced on the field of displacement discontinuities between elements. The resulting dense matrix discretizing the elastic equations is condensed using a hierarchical approximation that allow us to significantly speed up algebraic operations and, at the same time, reduce the memory requirements of such a computationally demanding matrix (see [6]). The fluid continuity equation combined with Darcy's law inside the fracture(s) is discretized spatially using a continuous Galerkin finite element (with linear shape functions).

We have notably implemented two solver(s) – which uses the same underlying building blocks:

- A one-way coupled solver, where the fluid flow is not influenced by the mechanical deformation. Such a solver is adequate to treat the case of constant permeability to compute the associated slip. It is not however capable of simulating the effect of shear-induced dilatancy on the increase of flow transmissivity.
- A two-way fully coupled solver, where fluid pressure influences mechanical deformation and mechanical deformation influences the flow (notably via non-linear variation of permeability and storage). This solver simulates the effect of shear-induced dilation on the increase of the fracture flow transmissibility. It can even capture the potential mechanical opening – and as such transition from hydro-shearing to hydraulic fracturing.

In both solvers, we use a fully implicit time-discretization. The resulting non-linear system of equations is solved via a Newton-Raphson scheme to obtain the increment of the pore-pressure values at the nodes of the mesh and the increment of displacement discontinuities at collocation points. For an elasto-plastic like constitutive law, the Newton-Raphson iterations require the computation of the so-called 'consistent tangent operator' of elastoplasticity (e.g. [7]) that we derive analytically for all interface constitutive models implemented. The activation and computation of fault slip is determined via the elastic predictor-plastic corrector (or sometimes called radial return mapping) algorithm of elastoplasticity (e.g. [7]). A complete technical description of the mathematical formulation of the model and algorithms used to solve it are described in a technical appendix to this report.

2.4 Codes repositories

The numerical solver developed during this project relies on a boundary element solver developed at the Geo-Energy Lab: BigWham. This code will be released under an open-source licence in the coming months. It will be available at the following URL:

https://github.com/GeoEnergyLab-EPFL/BigWham (as of now, to access this repo, send us a request)

In addition, the complete solver (and its documentation) for hydraulic stimulation (denoted as PyFracX – the X hinting that it can simulated multiple fractures) is available – upon request – at the following URL

https://github.com/GeoEnergyLab-EPFL/PyFracX

In addition, all the scripts for the verification examples of the solver are documented at the following repository:

https://github.com/GeoEnergyLab-EPFL/PyFracX-Examples

3 Results and discussion

3.1 Code Verification – a state of art series of must-passed test for fluid-driven fracture growth simulation

The simulation of fluid-driven fractures is known to be notoriously difficult, especially in relation to the strong coupling between fluid and solid mechanics as well as the moving boundary nature of fracture propagation. Proper verification over multiple order of magnitude of injection duration, for widely different in-situ conditions is a must.

In parallel of the numerical developments, we have also obtained a series of important semi-analytical solutions for the propagation of fluid-driven frictional ruptures. These analytical solutions have been obtained with additional assumptions (for example – constant flow properties of the fracture) for some simple fracture geometries (2D plane-elasticity or 3D axi-symmetry) and injection schedule (constant injection rate, or constant injection pressure). We refer to the papers of Sáez et al (2022, 2023) for detailed presentation of these solutions. These solutions for the growth of frictional ruptures driven by fluid injection complements the ones obtained for hydraulic fracture growth (see Detournay (2016) for review).

As a result, the developed numerical solver has been verified against the most in-depth suite of verification tests available to date for fluid-driven fractures growth. Table 1 list the different semi-analytical solutions that the code has been verified against. Note that the scripts of these different verifications are an intrinsic part of a series of documented examples of the code base.

Table 1 Series of reference solutions for fluid-driven ruptures propagation against which the developed numerical code has been successfully tested.

Geometry	Interface mechanics	Interface flow	Injection condition	Reference for the solution
2D plane-elasticity	Constant friction	Constant properties	Constant pressure	Viesca (2021), Bhattacharya & Viesca (2019)
2D plane-elasticity	Constant friction	Constant properties	Constant rate	Sáez *et al.* (2022)
2D plane-elasticity	Linear weakening friction	Constant properties	Constant pressure / constant rate	Garagash & Germanovich (2012)
2D plane-elasticity	Linear weakening friction with dilatancy	Constant properties	Constant pressure / constant rate	Ciardo & Lecampion (2019)
2D plane-elasticity	Tensile opening mode with zero cohesion	Cubic law	Constant rate	Adachi & Detournay (2002), Garagash & Detournay (2005)
3D axisymmetry	Constant friction	Constant properties	Constant rate/constant pressure	Sáez *et al.* (2022)
3D axisymmetry	Linear weakening friction	Constant properties	Constant rate/constant pressure	Sáez & Lecampion (2023)
3D axisymmetry	Tensile opening mode with zero cohesion	Cubic law	Constant rate	Savitski & Detournay (2002)

3.2 Three-dimensional growth of fluid-driven frictional ruptures

Abstract of “A. Sáez, B. Lecampion, P. Bhattacharya, and R. Viesca. Three-dimensional fluid-driven stable frictional ruptures. *J. Mech. Phys. Sol.*, 160:104754, 2022.”

We have investigated the quasi-static growth of a fluid-driven frictional shear crack that propagates in mixed mode (II+III) on a planar fault interface that separates two identical half-spaces of a three-dimensional solid. The fault interface is characterized by a shear strength equal to the product of a constant friction coefficient and the local effective normal stress. Fluid is injected into the fault interface and two different injection scenarios are considered: injection at constant volume rate and injection at constant pressure. We derive analytical solutions for circular ruptures which occur in the limit of a Poisson’s ratio ν =0 and solve numerically for the more general case in which the rupture shape is unknown (ν ≠ 0). For an injection at constant volume rate, the fault slip growth is self-similar. The rupture radius (ν =0) expands as R(t) = λ L(t) , where L(t) is the nominal position of the fluid pressure front and λ is an amplification factor that is a known function of a unique dimensionless parameter T . The latter is defined as the ratio between the distance to failure under ambient conditions and the strength of the injection. Whenever λ>1 , the rupture front outpaces the fluid pressure front. For ν ≠ 0 , the rupture shape is quasi-elliptical. The aspect ratio is upper and lower bounded by 1/(1- ν) and (3- ν) /(3-2 ν) , for the limiting cases of critically stressed faults ($\lambda \gg 1, T \ll 1$) and marginally pressurized faults (($\lambda \ll 1, T \gg 1$), respectively. Moreover, the evolution of the rupture area is independent of the

Poisson's ratio and grows simply as $A_r(t) = 4\pi\alpha\lambda 2 t$, where α is the fault hydraulic diffusivity. For injection at constant pressure, the fault slip growth is not self-similar: the rupture front evolves at large times as $\propto (\alpha t)^{(1-T)/2}$ with T between 0 and 1. The frictional rupture moves at most diffusively ($\propto \sqrt{\alpha t}$) when the fault is critically stressed, but in general propagates slower than the fluid pressure front. Yet in some conditions, the rupture front outpaces the fluid pressure front. The latter will eventually catch the former if injection is sustained for a sufficient time. Our findings provide a basic understanding on how stable (aseismic) ruptures propagate in response to fluid injection in 3-D. Notably, since aseismic ruptures driven by injection at constant rate expands proportionally to the squared root of time, seismicity clouds that are commonly interpreted to be controlled by the direct effect of fluid pressure increase might be controlled by the stress transfer of a propagating aseismic rupture instead. We also demonstrate that the aseismic moment M_o scales to the injected fluid volume V as $M_o \propto V^{3/2}$.

3.3 Post-injection aseismic slip as a mechanism for the delayed triggering of seismicity

Abstract of A. Sáez and B. Lecampion. Post-injection aseismic slip as a mechanism for the delayed triggering of seismicity. Proceedings of the Royal Society A, 479(2273):20220810, 2023.

Injection-induced aseismic slip plays an important role in a broad range of human-made and natural systems, from the exploitation of geo-resources to the understanding of earthquakes. Recent studies have shed light on how aseismic slip propagates in response to continuous fluid injections. Yet much less is known about the response of faults after the injection of fluids has stopped. In this work, we investigate via a hydro-mechanical model the propagation and ultimate arrest of aseismic slip during the so-called post-injection stage. We show that after shut-in, fault slip propagates in pulse-like mode. The conditions that control the propagation as a pulse and notably when and where the ruptures arrest are fully established. In particular, critically-stressed faults can host rupture pulses that propagate for several orders of magnitude the injection duration and reach up to nearly double the size of the ruptures at the moment of shut-in. We consequently argue that the persistent stressing of increasingly larger rock volumes caused by post-injection aseismic slip is a plausible mechanism for the triggering of post-injection seismicity ---a critical issue in the geo-energy industry. Our physical model shows quantitative agreement with field observations of documented cases of post-injection induced seismicity.

3.4 Fluid-driven slow slip and earthquake nucleation on a slip-weakening circular fault

Abstract of A. Sáez and B. Lecampion. Fluid-driven slow slip and earthquake nucleation on a slip-weakening circular fault. *J. Mech. Phys. Sol.*, (2024)."

Following the work of *Sáez et al* (2022) who examined the three-dimensional propagation of injection-induced stable frictional sliding on a constant-friction fault interface separating two identical elastic solids, we extend their model to account for a friction coefficient that weakens with slip. This enables the model to develop a proper cohesive zone besides incorporating a finite amount of fracture energy, both ingredients absent in the former model. To do so, we consider two friction laws characterized by a linear and an exponential weakening of friction respectively. We focus on the particular case of axisymmetric circular shear ruptures as they capture the most essential aspects of the dynamics of unbounded ruptures in three dimensions. It is shown that fluid-driven slow slip can occur in two distinct modes in this model: as an interfacial rupture that is unconditionally stable, or as the quasi-static nucleation phase of an otherwise dynamic rupture. Whether the interface slides in one way or the other depends primarily on the sign of the difference between the initial shear stress (τ_o) and the in-situ residual strength (τ_r^o) of the fault. For ruptures that are unconditionally stable ($\tau_o < \tau_r^o$), fault slip undergoes four distinct stages in time. Initially, ruptures are self-similar in a diffusive manner and the fault interface behaves as if it were governed by a constant friction coefficient equal to the peak (static) friction value. Slip then accelerates due to frictional weakening while the cohesive zone develops. Once the latter gets properly localized, a finite amount of fracture energy emerges along the interface and the rupture dynamics is governed by an energy balance of the Griffith's type. We show that in this stage, fault slip always transition from a large-toughness to a small-toughness regime due to the diminishing effect of the fracture energy in the near-front energy budget as the rupture grows. Moreover, while slip grows likely confined within the pressurized region in prior stages, here the rupture front can largely outpace the pressurization front if the fault is close to the stability limit ($\tau_o \approx \tau_r^o$). Ultimately, self-similarity is recovered and the fault behaves again as possessing a constant friction coefficient, but this time equal to the residual (dynamic) friction value. It is shown that in this ultimate regime, the fault interface operates to leading order with zero fracture energy. On the other hand, when slow slip propagates as the nucleation phase of a dynamic rupture ($\tau_o > \tau_r^o$), fault slip also initiates in a self-similar manner and the interface operates at a constant peak friction coefficient. The maximum size that aseismic ruptures can reach before becoming unstable (inertially dominated) can be as small as a critical nucleation radius equal to the shear modulus divided by the slip-weakening rate, and as large as infinity when faults are close to the stability limit ($\tau_o \approx \tau_r^o$). The former case corresponds to faults that are critically stressed before the injection starts, in which case ruptures always expand much further away than the pressurized region. The larger the critical nucleation radius is with regard to the cohesive zone size; the longer ruptures can accelerate aseismically before becoming unstable. When the nucleation radius is smaller than the cohesive zone size, aseismic ruptures accelerate upon departing from the self-similar response due to continuous frictional weakening over the entire slipping region, undergoing nucleation unaffected by the residual fault strength. Conversely, when the nucleation radius is (much) larger than the cohesive zone size, aseismic ruptures transition towards a stage controlled by a front-localized energy balance and undergo nucleation in a `crack-like' manner. Our results include analytical and numerical solutions for the problem solved over its full dimensionless parameter space, as well as expressions for relevant length and time scales characterizing the transition between different stages and regimes. Due to its three-dimensional nature, the model enables quantitative comparisons with field observations as well as preliminary engineering design of hydraulic stimulation operations. Existing laboratory and in-situ experiments of fluid injection are briefly discussed in this paper.

3.5 Maximum size and magnitude of injection-induced slow slip events

Abstract of A. Sáez, F. Passelègue, B. Lecampion. Maximum size and magnitude of injection-induced slow slip events. Submitted to *Science Advances* (2024)

Fluid injections can induce aseismic slip, resulting in stress changes that may propagate faster than pore pressure diffusion, potentially triggering seismicity at significant distances from injection wells. Constraining the maximum extent of these aseismic ruptures is thus important for better delineating the influence zone of injections concerning their seismic hazard. Here we derive a scaling relation based on rupture physics for the maximum size of aseismic ruptures, accounting for fluid injections with arbitrary flow rate histories. Moreover, based on mounting evidence that the moment release during these operations is often predominantly aseismic, we derive a scaling relation for the maximum magnitude of aseismic slip events. Our theoretical predictions are consistent with observations over a broad spectrum of event sizes, from laboratory to real-world cases, indicating that fault-zone storativity, background stress state, and injected fluid volume are key determinants of the maximum size and magnitude of injection-induced slow slip events.

3.6 Sequential multi-stage hydraulic stimulation simulations in the Haute-Sorne context

We have used an axisymmetric model of hydro-shearing of a pre-existing fracture using the “potential” configuration of Haute-Sorne (in terms of plausible in-situ stress and rock properties) for a preliminary injection schedule. We have then estimated the effect of such a stage on subsequent ones (assuming parallel pre-existing fractures). We have performed a number of examples to demonstrate the capability of the numerical solver in a 3D staggered-injection scenario similar to the Haute-Sorne configuration. As an example, we have simulated the cases of two fractured planes at some distance from each other in an infinite isotropic elastic medium. We discretised these fractured planes with triangular elements and use our fully couped hydro-mechanical solver to solve the staggered injection scenario accounting for fracture permeability changes (and weakening of friction). First, we injected in first plane for some hours, and, after some time, we stop injecting in the first plane and started to inject in the second plane and so on. We can observe the pulse-like slip propagation in the first plane after shut-in and crack-like slip propagation in the second plane once injection is started in it. The numerical model naturally accounts for the elastic interaction between the different stimulated fractured planes, which is important to study the permeability changes and seismic hazard analysis associated with the Haute-Sorne muti-stage injection. The results are reported in appendix C.

3.7 Modeling of the Basel-1 well hydraulic stimulation

We have first re-analysed the pre-stimulation test to estimate the initial equivalent hydraulic properties assuming a single fracture intersecting the wellbore. While analysing the data, we accounted for pressure drop in the injection well due to wellbore compressibility and a near wellbore skin. Using this approach, we fit the measured pressure at the wellbore to obtain the transmissivity and storage coefficient of an equivalent fracture. Also, by analysing the in-situ stress conditions from previous studies and evaluating the orientation of the potential slipping plane from the microseismical cloud, we have constraint the initial shear and normal effective stresses acting on a single fracture plane where the rupture is assumed to develop.

Then, we have built a fully coupled model for the case of the re-activation of a single fracture plane in axi-symmetry accounting for the following effects: dilatancy, frictional weaking, and permeability changes due to fracture deformation. This axisymmetrical model is able to properly reproduce the overall behavior of the wellhead pressure changes as well as the migration of the induced micro-seismicity.

Subsequently, we have built a 3D model accounting for the different fracture planes where micro-seismic events have occurred.

A paper is currently under preparation on the reproduction of the Basel-1 stimulation. The technical details and results are reported in appendix C.

3.8 Modeling of the Utah Forge 2022 hydraulic stimulations

We have also analyzed stages 2 and 3 performed in April 2022 at UTAH Forge. In view of the available data (wellhead pressure and located micro-seismic events), we decided first to build an axisymmetric model for each stage. We notably found that stage 3 is likely a pure hydraulic fracture, while stage 2 may be a mix of both shear and tensile ruptures. These models capture qualitatively the evolution of the wellhead pressure and microseismic events evolution. However, these models underestimate the recorded pressure by a large amount (over 15MPa) which is likely due to a high fracture tortuosity in the near-wellbore and/ or possibly a large under-estimation of the in-situ stress. In view of the coarse accuracy of the microseismic event localization, building a 3D model does not appear to be relevant at this point.

A technical report analyzing and modelling two stages (stages 2 and 3) of the Utah Forge 2022 hydraulic stimulations is attached in appendix D.

3.9 Other hydraulic stimulations

We have also revisited two others hydraulic stimulation performed for geothermal reservoirs development: the 1993 hydraulic stimulation performed in the GPK-1 well at Soultz-sous-Forêts, and the 2013 stimulation performed in the GRT-1 well at Rittershoffen. These examples are notably interesting with respect to the migration of microseismicity after the end of the injection (shut-in phase). We have clearly shown that the fluid-driven frictional shear crack model explain the rupture evolution as imaged by the migration of micro-seismic events – this using well-accepted parameters for these sites. The complete discussion of these two cases can be found in the article "Post-injection aseismic slip as a mechanism for the delayed triggering of seismicity" published in the *Proceedings of the Royal Society*, (Sáez & Lecampion, 2023).

4 Conclusions

Over the course of this project, we have developed robust numerical schemes for the physics-based modeling of hydraulic stimulation in both 2d and 3D. In addition, we have solved analytically a number of problems related to the growth of frictional / shear ruptures relevant for hydro-shearing stimulation– therefore providing invaluable benchmarks to our numerical solver, but also tremendous physical insights. The numerical code developed has been thoroughly tested, which has allowed to gain confidence in its predicting capabilities.

The numerical solver developed was also able to reproduce field measurements (pressure, rupture evolution as imaged by micro-seismicity evolution) of the hydraulic stimulation of the Basel-1 well. The 2022 hydraulic stimulation stages performed at Utah Forge were also analyzed and modelled. The theoretical model was also applied to others well-documented hydraulic stimulation (Soultz-sous-Fôret, Ritthershofen). It has allowed to notably quantify the importance of post shut-in aseismic growth under critically stressed conditions – a fact that must be recognized in order to put in perspective the promises of the so-called traffic light systems. More fundamentally, this theoretical model provides an upper bound for the moment magnitude and rupture size of fluid-induced slow slip events.

The model was also used to simulate a sequence of hydraulic stimulations performed at different location along a well via packer-systems. The numerical solver naturally accounts for the stress interaction associated with such a sequence of hydraulic stimulation treatments. In its current form, the model can be used by an expert in the field of numerical modeling in geomechanics after proper training. It allows to predict, for given initial stress condition and rock mass properties, the impact of hydraulic stimulation on frictional ruptures of pre-existing fractures and the subsequent increase of permeability. As such, it can be used within engineering workflow to test injection scenario – although it would benefit from improved numerical performance.

5 Outlook and next steps

Development of robust numerical codes for the simulation of geomechanical processes takes years to mature. The capabilities developed over the course of this project are unique – and we are not aware of commercial codes being able to model at the same time and spatial resolution the propagation of frictional ruptures growth driven by fluid injection. More importantly than the numerical solver itself, the knowledge developed during the course of the EMOD project can be directly applied to the design of hydraulic stimulation. For example, for a given geological configuration (fractures orientation, in-situ stress field, fracture hydraulic properties), the extent of the stimulation can be directly estimated to first order by calculating the fault-stress injection parameter T – to decipher between critically stressed and marginally pressurized conditions and bound the injection rates to be used via the semi-analytical solution presented in Sáez et al. (2022) and Sáez et al. (2024) for arbitrary injection schedule. In a second stage, the fully coupled hydromechanical model allow to estimate the increase of the fracture permeability and thus the ultimate increase of reservoir transmissivity. We have seen that although fracture permeability changes impact injection pressure to first order, the extent of the rupture is not significantly impacted by fracture permeability increase.

The maturity of the numerical code is not yet sufficient for widespread deployment – especially in its 3D version which is not sufficiently computationally efficient. It is still a research code, which require a fair amount of expertise to i) run simulations and ii) analyze their results. In order to push the use of this tool into practice, the following efforts will be essential:

1. Training of potential users. In order to increase its use, providing in-depth technical training to potential users will be required. Our experience has shown that hydrogeologist and geophysicist lacks the proper technical background associated with fracture and geomechanics to easily understand the parameters affecting the propagation of fluid-induced ruptures. A 5 days intensive hands-on training will be a minimum.
2. Improvement of the useability of the code. Software developments to improve the definition, preparation and monitoring of simulations are required in a first place. Similarly, software tools to allow the import of discrete fracture network geometry, well trajectory but also to scripts to simplify the analysis of the results of the code by non-python experts would be a plus.
3. Deployment of modern software engineering workflow (Continuous integration, Regression testing etc.) would benefit long-term code maintenance.
4. Code speed-up. The use of distributed memory computed throughout the code appears essential to allow very large-scale simulations of the injection into densely fractured rock mass in 3D. Such an effort will take several years full-time equivalent of a high-performance computing expert.
5. Code documentation & libraries of examples. Additional efforts are required to increase the technical documentation of the code, and provide additional examples of simulations that can be performed by such a code.

In parallel, a number of additional physics would be interesting to further include in the model – notably: i) matrix flow, ii) matrix poroelasticity, iii) thermal effects etc. Several years of effort will be required to develop robust code for each of these.

6 National and international cooperation

The EMOD project is related to both the SPINE and DEEP projects funded by the Swiss Federal Office of Energy SFOE as innovation components of the EGS project in Haute-Sorne, canton of Jura, led by Geo-Energie Suisse AG (contract number MF-021-GEO-ERK). As a result, teams from these projects were invited to attend our monthly meetings for exchanging information. In addition, the EMOD project had synergies with some modeling effort at ETH Zurich on the FEAR project. Notably F. Ciardo (ETH-Z) is an ex-PhD student of our group at EPFL. Federico has been using the numerical solver developed as part of EMOD, and has given significant feedbacks. Note that Federico has just been appointed as Assistant Professor at Northwestern University, IL, USA.

Internationally, we have collaborated with the following researchers on the broad topic of fluid-induced shear crack growth:

- Prof. Dmitry Garagash, Dalhousie University (Canada)
- Prof. Robert Viesca, Tufts University (USA)
- Prof. Pathikrit Bhattacharya, NISER Bhubaneswar (India)

Alexis Sáez PhD thesis was partly funded by the EMOD project. Alexis is now post-doctoral associated at Caltech in the group of Prof.J-P Avouac.

7 Communication

In addition to numerous presentations at international conferences (EGU, US Rock Mechanics symposia) listed under the publications section, we have organized a two days' workshop on well stimulation by hydraulic fracturing on June 8-9, 2023. The event was attended by 25 participants (Engineering firm, governmental authorities etc.).

8 Deviations

It was initially thought that we would model injection performed in the Bedretto URL. After discussions with the different stakeholders of the project, it was decided that project time would be better spent in reproducing the 2022 Utah Forge simulations. Another deviation worth noting is related to the incorporation of fluid leak-off in the model. The implementation of leak-off was abandoned in order to focus on the modeling of past-injections. As the first well of the Haute-Sorne project was only completed at the end of the project, the tool developed here was only used for hypothetical simulations as the actual knowledge of the hydro-geomechanical parameters was not available.

9 Publications

Journal papers

A. Sáez, B. Lecampion. Fluid-driven slow slip and earthquake nucleation on a slip-weakening circular fault, *J. Mech. Phys. Sol.*, page 105506, 2024. https://doi.org/10.1016/j.jmps.2023.105506

A. Sáez and B. Lecampion. Post-injection aseismic slip as a mechanism for the delayed triggering of seismicity. *Proceedings of the Royal Society A*, 479(2273):20220810, 2023. https://doi.org/10.1098/rspa.2022.0810

F. Ciardo and B. Lecampion. Injection-induced aseismic slip in tight fractured rocks. *Rock Mechanics and Rock Engineering*, pages 1–22, 2023. https://doi.org/10.1007/s00603-023-03249-8

A. Sáez, B. Lecampion, P. Bhattacharya, and R. Viesca. Three-dimensional fluid-driven stable frictional ruptures. *J. Mech. Phys. Sol.*, 160:104754, 2022. https://doi.org/10.1016/j.jmps.2021.104754

Submitted Paper

A. Sáez, F. Passelègue, B. Lecampion. Maximum size and magnitude of injection-induced slow slip events. Under review *Science Advances* (2024)

Papers in preparation

A. Sáez, B. Lecampion "Spatiotemporal signatures of seismic swarms driven by fluid injections and induced aseismic slip"

Lecampion B., Gupta A., Sáez A., Fakhretdinova R., Sarma A., Brisson S. ‘Simulation of fluid-driven ruptures along pre-existing discontinuities in impermeable rocks: accuracy and robustness in light of novel verification examples’ to be submitted to *Comp. Meth. Appl. Mech. Eng.*

Fakretdinova R., Alcolea A., Sáez A. and Lecampion, B. ‘Hydro-mechanical modeling of the Basel-1 well hydraulic stimulation’ to be submitted to *Int. J. Rock Mech. Min. Sci.*

Conference papers

Brisson S. and Lecampion B. “Hydraulic fracturing or hydro-shearing during the 2022 Utah Forge stimulation” to be submitted to the 59th US Rock Mechanics symposium – ARMA 2025.

B. Lecampion, A. Sáez, and A. Gupta. Shearing and opening of a pre-existing discontinuity in response to fluid injection. In *57th US Rock Mechanics/Geomechanics Symposium*, number ARMA 23-721, Atlanta, GA, USA, June 25–28 2023.

Talks & Conference abstracts

B. Lecampion. "Fluid-driven ruptures - From Hydraulic Fractures to Fluid-induced Fault Slip". **Keynote Lecture** at the 58th US Rock Mechanics Symposium (ARMA 24) held in Golden, Colorado, June 23-26 2024.

Fakhretdinova R., Sáez A., Alcolea A., and Lecampion B. Revisiting the Basel-1 hydraulic stimulation with a coupled hydro-mechanical model: Preliminary results. Talk presented at the *GEoREST Workshop on Induced Seismicity*, Palma de Mallorca, Spain, 11–13 March 2024.

Sáez, A. and Lecampion, B.: Reactivation of fault slip during and after fluid injections: theoretical considerations, micro-seismicity patterns, and aseismic moment release. **Invited Talk** presented at the *GEoREST Workshop on Induced Seismicity*, Palma de Mallorca, Spain, 11–13 March 2024.

Sáez, A. and Lecampion, B.: Extraction of fluids to mitigate the seismic risk associated with post-injection aseismic slip, EGU General Assembly 2023, Vienna, Austria, 23–28 Apr 2023, EGU23-15861, https://doi.org/10.5194/egusphere-egu23-15861, 2023.

Fakhretdinova, R., Sáez, A., and Lecampion, B.: The effect of in-situ linear stress gradient on the frictional shear rupture growth in 2D., EGU General Assembly 2023, Vienna, Austria, 23–28 Apr 2023, EGU23-15244, https://doi.org/10.5194/egusphere-egu23-15244, 2023.

Lecampion, B., Sáez, A., Fakhretdinova, R., and Gupta, A.: Development of a robust numerical simulator for mixed shear and opening modes fluid driven fracture propagation along pre-existing discontinuities, EGU General Assembly 2023, Vienna, Austria, 23–28 Apr 2023, EGU23-16563, https://doi.org/10.5194/egusphere-egu23-16563, 2023.

B. Lecampion, A. Sáez, and R. Fakhretdinova. Numerical simulations of mixed shear and opening modes fluid driven fracture propagation on pre-existing discontinuities. In *The 8th European Congress on Computational Methods in Applied Sciences and Engineering, ECCOMAS Congress 2022*, Oslo, Norway, 5–9 June 2022.

Lecampion B., Sáez A., Fakhretdinova R. (2022). 2D & 3D numerical modelling of fluid-driven frictional crack growth for geothermal hydraulic stimulation EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-11543.

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A. Saez and B. Lecampion. Post-injection aseismic slip as a mechanism for the delayed triggering of seismicity. *Proceedings of the Royal Society A*, 479(2273):20220810, 2023.

A. Saez, B. Lecampion, P. Bhattacharya, and R. Viesca. Three-dimensional fluid-driven stable frictional ruptures. *J. Mech. Phys. Sol.*, 160:104754, 2022.

A. Savitski and E. Detournay. Propagation of a penny-shaped fluid-driven fracture in an impermeable rock: asymptotic solutions. *International Journal of Solids and Structures*, 39(26):6311–6337, dec 2002.

R. C. Viesca. Self-similar fault slip in response to fluid injection. *Journal of Fluid Mechanics*, 928:A29, 2021.

11 Appendices

Appendix A: Technical description of the mathematical formulation and numerical algorithms of the developed numerical solver.

Appendix B: Technical report on sequential hydro-shearing stimulation along a wellbore in the context of Haute-Sorne.

Appendix C: Draft of a publication on the simulation of the Basel-1 well hydraulic stimulation.

Appendix D: Technical report of the analysis and modelling of the 2022 Utah FORGE hydraulic stimulation.

Appendix E: Research publications published during this research project.