Ph.D. Thesis

PROCESS UNDERSTANDING OF INDUCED SEISMICITY DURING STIMULATION OF ENHANCED GEOTHERMAL SYSTEMS

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To my parents, Fazlollah & Fereshteh and my siblings, Reza, Maryam, & Ahmad

Abstract

This doctoral thesis investigates the causes that induce (micro)seismicity as a result of hydraulic stimulation in fractured low-permeability rock. Understanding such phenomenon is of paramount importance to eventually forecast induced seismicity in geoenergy applications, like Enhanced Geothermal Systems (EGS). The research is driven by both scholarly and engineering considerations, addressing the intricate coupled hydromechanical (HM) processes that are at play and aiming to advance in the understanding of the mechanisms underlying co-seismicity during the hydraulic stimulation phase of EGS.

The thesis begins with a comprehensive review of existing modeling methodologies of coupled processes in fractured rock. This exploration highlights the significant advancements these methodologies have brought to the foundational understanding of fractures, ultimately improving predictive capabilities related to coupled processes within fractured systems.

The subsequent focus of the research involves an investigation into the flow regimes induced by constant flow rate water injection into a fracture surrounded by a lowpermeability matrix. The study sheds light on the implications for hydraulic test interpretation and numerical simulations. The findings reveal that even in very lowpermeability confining rock matrix, leakage is non-negligible due to the small fracture aperture, which maximizes pressure gradients across the fracture-matrix interface. The transition between flow regimes, often overlooked in field tests, has important implications for accurately estimating fracture transmissivity in injection tests in fractured media and modeling approaches.

The thesis then proposes an innovative approach for the implicit representation of fractures surrounded by low-permeability rock matrix. This approach assimilates fractures as equivalent continua, demonstrating that a relatively thick equivalent continuum layer can accurately represent a fracture and reproduce HM behavior. The proposed method is validated through the modeling of a hydraulic stimulation carried out at the Bedretto Underground Laboratory, showcasing its ability to improve the simplicity and efficacy of continuum methods in representing fractures in fractured media. Finally, the research delves into the modeling of a highly-monitored test at the Bedretto Underground Laboratory to investigate the impact of fluid injection on permeability enhancement and induced microseismicity. Three models are examined, with the viscoplastic fracture with dilatancy and strain-weakening approach emerging as the most comprehensive in capturing the spatio-temporal coupled response of fractured rock to hydraulic stimulation. This model proves effective in estimating the extent of the stimulated fracture, permeability enhancement, and its impact on the local state of stress and pore pressure at surrounding fractures, presenting a valuable tool for the design of effective hydraulic stimulation.

In summary, this doctoral thesis contributes to the understanding of micro-seismicity induced by EGS operations, offering insights into coupled processes, flow regimes, and innovative modeling approaches, ultimately advancing the field of geothermal energy research and hydraulic stimulation design.

RESUMEN

Esta tesis doctoral investiga las causas que inducen la (micro)sismicidad como resultado de la estimulación hidráulica en rocas fracturadas de baja permeabilidad. Comprender este fenómeno es de vital importancia para prever la sismicidad inducida en aplicaciones geoenergéticas, como los sistemas geotérmicos mejorados (EGS por sus siglas en inglés). La investigación está impulsada por consideraciones tanto académicas como ingenieriles, abordando los intrincados procesos hidromecánicos (HM) acoplados que entran en juego y con el objetivo de avanzar en la comprensión de los mecanismos subyacentes a la cosismicidad durante la fase de estimulación hidráulica de los EGS.

La tesis comienza con una revisión exhaustiva de las metodologías de modelización existentes de los procesos acoplados en rocas fracturadas. Esta exploración pone de relieve los importantes avances que estas metodologías han aportado a la comprensión fundamental de las fracturas, mejorando en última instancia las capacidades de predicción relacionadas con los procesos acoplados dentro de los sistemas fracturados.

A continuación, la investigación se centra en los regímenes de flujo inducidos por la inyección de agua a caudal constante en una fractura rodeada por una matriz de baja permeabilidad. El estudio arroja luz sobre las implicaciones para la interpretación de ensayos hidráulicos y simulaciones numéricas. Los resultados revelan que, incluso en una matriz de roca confinante de muy baja permeabilidad, las fugas no son despreciables debido a la pequeña abertura de la fractura, que maximiza los gradientes de presión a través de la interfaz fractura-matriz. La transición entre regímenes de flujo, que a menudo se pasa por alto en los ensayos de campo, tiene importantes implicaciones para estimar con precisión la transmisividad de la fractura en las pruebas de inyección en medios fracturados y en los planteamientos de modelización.

A continuación, la tesis propone un enfoque innovador para la representación implícita de fracturas rodeadas por una matriz rocosa de baja permeabilidad. Este enfoque asimila las fracturas como medios continuos equivalentes, demostrando que una capa de medio continuo equivalente relativamente gruesa puede representar con precisión una fractura y reproducir el comportamiento HM. El método propuesto se valida mediante la modelización de una estimulación hidráulica llevada a cabo en el Laboratorio Subterráneo de Bedretto, mostrando su capacidad para mejorar la simplicidad y eficacia de los métodos continuos en la representación de fracturas en medios fracturados.

Por último, la investigación profundiza en la modelización de una prueba altamente monitorizada en el Laboratorio Subterráneo de Bedretto para investigar el impacto de la inyección de fluidos en el aumento de la permeabilidad y la microsismicidad inducida. Se examinan tres modelos, y el de fractura viscoplástica con dilatancia y debilitamiento por deformación resulta ser el más completo para captar la respuesta acoplada espaciotemporal de la roca fracturada a la estimulación hidráulica. Este modelo resulta eficaz para estimar la extensión de la fractura estimulada, la mejora de la permeabilidad y su impacto en el estado local de tensión y presión de poros en las fracturas circundantes, presentando una valiosa herramienta para el diseño de una estimulación hidráulica eficaz.

En resumen, esta tesis doctoral contribuye a la comprensión de la microsismicidad inducida por las operaciones EGS, ofreciendo una visión de los procesos acoplados, los regímenes de flujo y los enfoques de modelado innovadores, avanzando en última instancia en el campo de la investigación de la energía geotérmica y el diseño de la estimulación hidráulica.

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1

INTRODUCTION

1.1 Background and motivation

The contemporary surge in global greenhouse gas emissions persists unabated, a concerning trend amid the urgent need for a substantial reduction (*IPCC*, *Climate Change*, 2023). Comprehending the origins of these emissions and how we could eliminate them stand as a crucial step towards their effective abatement. We need to find answers to questions like: which industries wield the most significant influence? How might this discernment inform the development of pragmatic solutions and proactive mitigation strategies? Figure 1.1 shows the breakdown of total greenhouse gas emissions, quantified in metric tons of carbon dioxide (CO₂) equivalents, across various sectors by 2020. Notably, the data highlights the substantial dominance of electricity and heat production as the foremost contributors to the global emission footprint, followed by diverse sectors.

The necessary shift from the existing fossil-fuel-dependent energy structure toward a sustainable paradigm, grounded primarily on renewable resources, necessitates a robust foundation of evidence-based decision-making processes (Christensen and Hain, 2017). Within the realm of renewable energy sources tackling electricity and heat production, geothermal energy stands as a promising alternative owing to its minimal environmental footprint, low greenhouse gas emissions and, unlike other renewables, non-intermittent production (Shortall et al., 2015). Geothermal energy reservoirs, ubiquitously dispersed beneath the Earth's surface, exhibit economic viability hinged upon critical factors such as depth, permeability, and temperature. These reservoirs can be broadly categorized into shallow and low-temperature formations, and deep and high-temperature formations, the

latter often exceeding 100 °C and occasionally surpassing 400 °C, particularly within volcanic regions (Tomac and Sauter, 2018). While shallow geothermal energy, situated at relatively shallow depths and lower temperatures, is typically harnessed for direct applications like heating, deep geothermal energy, with its significantly elevated temperatures, finds application primarily in electricity generation (Bayer et al., 2019; Moya et al., 2018).



Figure 1.1 Greenhouse gas emissions by sector in the world, in 2020. Emissions are measured in carbon dioxide equivalents (CO_{2eq}). This means non- CO_2 gases are weighted by the amount of warming they cause over a 100-year timescale (ourworldindata.org). Electricity and heat production are the largest contributor to global emissions. This is followed by transport, manufacturing and construction (largely cement and similar materials), and agriculture

The viability of geothermal energy extraction from Hot Dry Rock (HDR) formations, primarily characterized by hard, low-permeable crystalline rock structures, necessitates the deployment of an Enhanced Geothermal System (EGS) capable of effectively converting geothermal energy into electricity (Olasolo et al., 2016). This involves the implementation of an intricate system of injection and production wells, engineered to stimulate fluid circulation and efficient heat extraction. Notably, hydraulic fracturing, in conjunction with hydroshearing, stands out as a key technology facilitating the establishment of stable and efficient flow paths for geothermal energy extraction (Hanano, 2004; Tangirala et al., 2023). Recent endeavors have underscored the feasibility of creating fluid-conducting fractures in both sedimentary and crystalline rock formations even at exceptionally high temperatures (>374 °C), setting the stage for the emergence of Enhanced Supercritical Geothermal Systems (Parisio et al., 2019).

However, the deployment of EGS faces challenges stemming from inadequate reservoir rock permeability and the potential for excessive induced seismicity during reservoir stimulation or operation. Subsurface fluid injection or extraction alters several crucial parameters of geological formations, including pore pressure, temperature, stress, and geochemical composition, often resulting in the destabilization of fractures and faults and subsequent seismic events. The connection between injection processes and induced seismic activity remains a subject of intense scientific inquiry, primarily due to the associated risks and uncertainties. Mismanagement of induced seismicity can yield widespread damage to surface structures, eliciting warranted criticism from regulatory bodies and the general public. Notably, induced earthquakes have led to the discontinuation of several geothermal projects, exemplified by instances such as Basel, in Switzerland, Sankt Gallen, in Switzerland, and Pohang, in Korea Republic (Grigoli et al., 2017) (Figure 1.2). Consequently, the anticipation and mitigation of potentially damaging induced seismicity, emerge as pivotal considerations in the successful execution of fluid injection projects, underscoring the necessity for an improved understanding of injectioninduced fault stability and risk management strategies (Vilarrasa et al., 2017a).



Figure 1.2 EGS may trigger unexpected induced seismic activity. If felt, induced seismicity has a negative effect on public perception and may jeopardize geoenergy infrastructure. It is necessary to reverse the damage that these incidents caused to public perception, since without geoenergy technologies, climate neutrality could be hardly reached.

Forecasting injection-induced seismic events presents a big challenge, demanding a comprehensive approach that integrates field-scale experiments and numerical simulations, thereby accounting for the pertinent physical processes. Addressing the knowledge gap spanning laboratory and reservoir scales is achievable through the implementation of controllable meso-scale in situ experiments (Amann et al., 2018a). Several underground research infrastructures, either repurposed from existing mines and tunnels or newly excavated (e.g., Åspö HRL, Sweden; Grimsel, Switzerland; Jinping, China, Kamaishi, Japan; KURT, South Korea; Mont Terri, Switzerland; Reiche Zeche, Germany) have been established for this purpose. The exposure of the subsurface environment facilitates direct access to deep-seated rock masses, enabling sophisticated multi-disciplinary characterization, instrumentation, and experimentation at elevated spatial resolutions and controllable scales that would otherwise be unattainable from the surface or through downhole instruments. Tailored to site-specific conditions, these infrastructures offer rock volumes ranging from decameters to hectometers, catering to diverse experimental objectives and providing desired levels of heterogeneity and complexity. As part of an effort to step up the scale towards hectometer rock masses, the Bedretto Lab for Geosciences and Geoenergies (BULGG) was established in 2018. It is located inside the Bedretto tunnel in the Canton of Ticino, Switzerland (Figure 1.3). The purpose of the BULG is to host reduced scale in-situ experiments in crystalline rocks, with focus on drilling and completion, hydraulic stimulation, monitoring and seismic risk mitigation during the construction of an EGS.



Figure 1.3 Oblique view of the Rotondo Granite in the Gotthard Massif and approximate location of BedrettoLab.

In the case of injection-induced seismicity, the prevailing triggering mechanism is conventionally ascribed to downhole overpressure, inducing a reduction in effective stresses and consequent diminution of frictional resistance (Hubbert and Rubey, 1959; Pearson, 1981; Raleigh et al., 1976). However, the intricate interplay of HM coupling introduces a layer of complexity to this behavior. The variation in pressure instigates modifications in the stress field and deformation of the reservoir, thereby influencing the ensuing pressure response (Rutqvist and Stephansson, 2003). To unravel these intricacies, mathematical modeling and numerical simulations are imperative. The crux of the challenge lies in the necessity for a proficient numerical model that accurately captures both the rock matrix and fractures, faithfully reproducing the HM response of the system for the precise prediction of induced seismicity. On the one hand, common approaches involve utilizing continuum models, encapsulating fractures as effective properties within the rock matrix. However, fractures, being dynamic entities, not only impose static constraints influencing fluid flow but also undergo evolutionary changes that alter the stress field. On the other hand, discontinuum approaches, historically neglectful of mechanics until recent advancements, present computational challenges due to their potential costliness. Therefore, the development of a numerical model that reconciles lesser computational cost and accuracy in representing both rock matrix and evolving fractures is indispensable for understanding induced seismicity.

Incorporating fractures into numerical simulations introduces several challenges, including the representation of fractures with substantial aspect ratios, numerical difficulties arising from micrometer-scale apertures juxtaposed with fractures spanning hundreds of meters (Berkowitz, 2002; Singhal and Gupta, 2010). Furthermore, fractures exhibit distinct properties and physical processes in contrast to the surrounding rock matrix, with significantly higher permeability and a pivotal role in inducing rock deformation (Guglielmi et al., 2015a; Hubbert and Rubey, 1959). The non-linear coupled multi-physics problems inherent to fractured porous media further compound the challenges.

Due to the reasons mentioned above, developing new conceptual models and numerical schemes for fractured rocks can be a tremendous task. Despite the efforts already given to fractured rocks, the development of reliable numerical methods and simulation tools validated against field-scale experimental data for fractured rocks remains a formidable challenge. This thesis tackles parts of these challenges by considering a progressive approach. Since largest earthquakes have been induced in crystalline rocks, like in EGS, we focus on modeling fractures within a very low-permeability matrix and we try to respond to these research questions:

- > What are the modeling methodologies of coupled processes in fractured rock and their respective strengths and weaknesses in terms of their modeling capabilities, computational precision and costs?
- ➤ How is the hydraulic behavior of a fracture embedded in a low-permeability matrix in response to fluid injection?
- ➤ How is elastic poromechanical behavior, considering both constant permeability and aperture-dependent variable permeability?
- > What are the mechanisms that may induce microseismicity during fracture stimulation?

We define the objectives of the thesis to find answers to these questions.

1.2 Thesis objectives

The aim of this Thesis is to investigate the processes that take place during the stimulation of EGS and that may induce seismicity. We aim at deepening the understanding of the involved hydro-mechanical (HM) processes, to explain and manage co-injection seismicity. To reach this goal, it is necessary to understand the coupled behavior of fractured rock masses. Several research questions linking induced seismicity to the HM response of the pre-existing fractures remain open. Our goal is to understand the poromechanical processes that occur within the stimulated fracture and its surrounding. Shedding light on the fundamental processes will allow us to reach the following specific objectives (SO):

- SO1: To carry out an extensive literature review on modeling of coupled processes in fractured rocks with focus on the various fracture representation approaches;
- SO2: To seek an approach to model fractures following continuum approaches as in, e.g., the finite element software CODE_BRIGHT, and to find equivalent properties to overcome the limiting effect of the extreme width-to-length ratio of fractures;
- SO3: To interpret flow tests in fractures, focusing on how the transmissivity and the storage coefficient should be estimated using the theory of hydrogeology;
- SO4: To investigate hydro-shearing and permeability enhancement of fractured rock at the Bedretto Underground Laboratory, Switzerland, and interpret field-scale data.

1.3 Thesis outline

Beyond the introductory and concluding chapters, the thesis is structured into 4 distinct chapters, each corresponding to articles currently (or soon) undergoing peer review for prospective publication. Each chapter is self-contained, commencing with its own introduction and culminating with a concluding section. Thus, the subsequent sections of the thesis follow the outlined structure as delineated below:

- provides an overview of diverse modeling approaches concerning coupled Chapter 2 processes in fractured rock formations. Its primary objective is to offer a comprehensive and integrated perspective on modeling methodologies, focusing on broader methodological categories rather than specific numerical techniques. The chapter highlights the strengths and weaknesses of these methods in terms of their modeling capabilities, precision, and associated computational costs. computational Additionally, it aims to enhance the reader's understanding of the various coupling schemes used in reservoir geomechanics, heat transfer, and fluid flow within fractured rock formations. The chapter contributes to give a holistic view of fundamental theoretical frameworks and modeling paradigms, while also emphasizing strategies for addressing current challenges and recent advancements in this field. Based on this extensive literature review an article titled 'A review on thermo-hydromechanical modeling of coupled processes in fractured rocks: A continuum to discontinuum perspective' has been developed and will be submitted to an international scientific journal.
- Chapter 3 presents the investigation of the flow regimes induced by constant flow rate water injection into a fracture surrounded by low-permeability matrix. The analysis of the pressure evolution reveals that leakage into the low-permeability rock matrix impacts fluid flow. Having analyzed the hydraulic response, implications of the leaky nature of fractures in hydraulic-test interpretation and modeling subsurface applications, the origin of the leaky nature of fractures, and the role of fracture size are discussed. This chapter resulted in an article, titled 'On the leaky nature of fractures in low-permeability rock', which is currently under review in an international scientific journal.

- Chapter 4 introduces an approach for the implicit representation of fractures surrounded by low-permeability rock matrix to accurately simulate HM coupled processes. The approach assimilates fractures as equivalent continua with a manageable scale (>>1 µm) that facilitates spatial discretization, even for large-scale models including multiple fractures. The approach has been validated through modeling a hydraulic stimulation carried out at the Bedretto Underground Laboratory in Switzerland by comparing numerical results against measured data. The contents of this chapter have been included in a manuscript, titled 'Implicit hydromechanical upscaling of fractures using a continuum approach', and is under review in an international scientific journal.
- Chapter 5 describes modeling of a highly-monitored test performed at the Bedretto Underground Laboratory to investigate the impact of fluid injection on permeability enhancement and induced microseismicity. It examines three models: (1) a homogeneous fracture whose transmissivity is manually calibrated to reproduce the observed pressure evolution at the injection borehole; (2) an elastic fracture approach, where transmissivity changes locally as a function of fracture aperture following the cubic law; and (3) a viscoplastic fracture approach with strain weakening and dilatancy that yields an additional permeability enhancement after shear reactivation. This Chapter has resulted in an article, titled 'Numerical modeling of hydraulic stimulation of fractured crystalline rock at the Bedretto Underground Laboratory for Geosciences and Geoenergies', which is currently under review in a scientific journal.

Chapter 6 summarize the most relevant outcomes of the thesis.

2

A REVIEW ON THERMO-HYDRO-MECHANICAL MODELING OF COUPLED PROCESSES IN FRACTURED ROCKS

2.1 Introduction

Fractured rock masses encompass multiple discontinuities across various length scales, ranging from pores and microfractures to joints and faults. These inherent discontinuities alter the properties of crustal rocks, making them anisotropic, inhomogeneous, and nonlinear materials (Katsuki et al., 2019; Wang et al., 2021; Zhao et al., 2021). The amalgamation of these geological features and the multitude of physical processes occurring during various engineering applications present grand challenges for modeling studies. Despite the substantial advancements in computational resources in recent years, including an explicit description of all the micro-, meso- and macro-scale features in a porous medium remains unfeasible. Thus, addressing these complexities requires simplifying assumptions in the modeling approach. A common assumption in continuum models is to consider the averaged characteristics of the microscale features without the need of representing the actual pore and micro-crack structure. The focus lies on determining the upscaled behavior of the medium, which becomes the primary quantity of interest in these modeling approaches. Nevertheless, both microscopic and macroscopic models are important and a holistic approach may consider both modeling approaches (e.g., hierarchical or multiscale modeling) to draw a more comprehensive understanding of the system.

The interplay among the processes of fluid flow, heat transfer, and stress/deformation in fractured rocks has received considerable attention in the fields of rock mechanics, geophysics, and geological/geotechnical engineering since the early 1980s (Birkholzer et al., 2019; Jing, 2003; Tsang, 1991, 1987). This interplay is typically called coupled thermohydro-mechanical (THM) processes to highlight that one process influences the initiation and progression of another. THM processes are particularly complex in fractured media because of the marked heterogeneity of properties and this is central across various applications encompassing both natural and engineered systems, such as geothermal energy exploitation, groundwater management, subsurface energy and waste storage, underground construction, nuclear waste disposal, and contaminant transport analysis. Even though the relative significance of distinct physical processes may vary among these applications, they can be conceptualized as a confluence of fluid flow, heat transfer, and deformation transpiring within both the porous rock matrix and fractures. Depending on the specific application, a subset of these processes may suffice, while others might necessitate the consideration of chemical and biosphere elements as well as seismic coupling; however, we limit our focus to THM coupled models in this review.

Substantial research endeavors have been dedicated to the development of various numerical modeling approaches and techniques in response to the escalating demand for harnessing natural subsurface resources and addressing concerns pertaining to subsurface contamination (Berkowitz, 2002; Kazemi, 1969; Pruess and Narasimhan, 1985; Rutqvist et al., 2002; Tsang, 1999, 1991; Warren and Root, 1963; Wu and Pruess, 1988). Over the past few decades, several mathematical modeling approaches have been developed (see section 2.3) entailing the formulation of conceptual fracture models that incorporate geometric information of the fracture-matrix system. These approaches involve the establishment of mass and energy conservation equations for fracture-matrix domains, which are subsequently solved through discrete nonlinear algebraic equations. These numerical solutions account for the coupling of fluid flow with other relevant physical processes. However, a critical challenge encountered in simulating coupled processes in fractured rock lies in effectively addressing the complex interaction between fractures and the surrounding matrix under diverse conditions. This fracture-matrix interaction significantly distinguishes the flow through fractured porous media from that observed in homogeneous or heterogeneous single-porosity porous media.

This chapter aims at offering a comprehensive and integrated perspective on modeling methodologies of coupled processes in fractured rock, refraining from an exhaustive exposition of specific numerical techniques. Instead, it delineates broader categories of methods, elucidating their respective strengths and weaknesses in terms of their modeling capabilities, computational precision and costs. Furthermore, this chapter seeks to furnish a thorough comprehension of the various coupling schemes employed in the context of reservoir geomechanics, heat transfer, and fluid flow within fractured rock. Particularly directed towards researchers who are newcomers to the field of modeling THM coupled processes within fractured rock, this chapter endeavors to impart fundamental theoretical frameworks and modeling paradigms, while also accentuating the strategies for addressing prevailing challenges and recent advancements within this field. We elucidate the theoretical concepts of coupled processes in Section 2.2, delving into an exploration of the multifaceted aspects of coupling mechanisms. In Section 2.3, we conduct a critical review of the conceptual models employed for representing fractured rock formations. Subsequently, Section 2.4 presents formulation foundation and governing equations for THM modeling. Lastly, the conclusions section of the chapter discerns extant research gaps and delineates prospective directions for future research endeavors.

2.2 Coupled processes in fractured rock

2.2.1 Multiphysical couplings

Both fluid pressure and temperature changes cause stress and strain variations, inducing porosity, fracture aperture and intrinsic permeability changes, which in turn impact the pressure and temperature fields. The temperature distribution and evolution depend on how fluids flow through the fractures and matrix blocks, which in turn is controlled by temperature because of the dependency of fluid density and viscosity on pressure, and especially on temperature. Figure 1.1 illustrates the couplings among mechanical, hydraulic, and thermal processes.



Figure 2.1 Schematic representation of coupled hydro-mechanical (HM), thermo-mechanical (TM) and thermo-hydrological (TH) processes prevailing in the stimulated zone around an injection well. For the sake of simplicity, HM and TM and TH couplings are illustrated separately on either side of the injection well and not superimposed.

2.2.1.1 Thermo-mechanical coupling

Two key mechanisms are responsible for the coupling between thermal and mechanical processes (Figure 2.1). The first mechanism is thermal expansion, which refers to the change in the volume of a material in response to a temperature change. The induced strain is proportional to the temperature change and the thermal expansion coefficient of the solid material,

$$\Delta \varepsilon^T = \alpha_s^T \Delta T, \tag{2.1}$$

where $\Delta \varepsilon^T$ is the strain change, α_s^T is the thermal expansion coefficient of the solid material and ΔT is the temperature change. This mechanism (expansion/contraction of rock) affects adjacent fractures, whose aperture could decrease/increase (McDermott et al., 2006). Temperature changes induce porosity changes, which are controlled by both the volumetric deformation and the variations in solid density (Vilarrasa et al., 2014). This change in pore volume induces pressure changes that may become significant in tight rock (Vilarrasa et al., 2021), affecting the distribution of pore pressure and, therefore, affecting the mechanical problem in terms of effective stresses. Additionally, constraints to deformations and/or differential thermal deformations generate thermal stress that may result in the creation of new cracks and in the activation/reactivation of pre-existing fractures (Zhou et al., 2010). In particular, cooling-induced thermal stress reduction may eventually induce seismicity (Jeanne et al., 2014; Kivi et al., 2022; Parisio et al., 2019).

The second mechanism responsible for coupling between the mechanical and thermal fields only impacts the fractures, i.e., thermally-induced aperture change (Cooper and Simmons, 1977). The opening or closing of fractures will alter the volume of fluid filling them in a saturated medium, leading to variations in the heat storage capacity, which is dependent on the fluid volume filling the discontinuities. Additionally, fracture transmissivity for flow is also impacted by the variation of fracture aperture, according to the cubic law (Witherspoon et al., 1980; Zimmerman and Bodvarsson, 1996). This mechanism has minor impacts on the matrix.

2.2.1.2 Hydro-thermal coupling

Two primary mechanisms contribute to the coupling between the hydraulic and thermal fields (Figure 2.1). The first mechanism stems from the variation of the fluid viscosity and density as a result of temperature changes, which result in variations in the fluid volume (because of density changes) and transmissivity (because of both density and viscosity variations) and, thus, modify the pressure distribution in the hydraulic field. Both density and viscosity decrease with increasing temperature (Huber et al., 2009). The changes in transmissivity also modify the fluid velocity field (Darcy velocities), which in turn modify the heat transport driven by fluid movement (advection) causing alterations in the temperature distribution (Nield and Bejan, 2017). Advection primarily impacts the temperature in fractures, as they serve as preferential pathways for fluid flow, enabling heat to be transported along them at higher velocity than through the porous medium. Nonetheless, the thermal front advances much behind the pressure perturbation front as the thermal diffusivity is typically two to three orders of magnitude lower than the hydraulic diffusivity (De Simone et al., 2017).

As the second mechanism, the temperature variation affects the fluid occupying the pores or fractures, leading to volume changes proportional to its coefficient of thermal expansion α_f^T . This change in fluid volume modifies the pressure distribution in the hydraulic field and, subsequently, the effective stresses in the mechanical field. However, it is important to note that thermal expansion of fluid primarily affects the hydraulic field.

2.2.1.3 Hydro-mechanical coupling

The hydro-mechanical interaction is a well-established concept in the field of geomechanics, with seminal contributions from (Terzaghi, 1925) and (Biot, 1941) for consolidation analysis. For saturated geomaterials, the fluid occupies both the pores and discontinuities of the fractured porous medium, leading to a reciprocal influence between the pressures (hydraulic problem) and the deformations (mechanical problem). The effective stress principle captures this mutual interaction, where the pressure affects the effective stress, causing deformation of both the porous rock matrix and fractures, and this deformation (matrix porosity and fracture aperture changes), in turn, affects storativity of the matrix and fractures (Figure 2.2). These changes in the hydraulic properties of the fractured media, in turn, affect the flow and pressure fields (De Simone and Carrera, 2017; Verruijt, 1969).



Figure 2.2 Thermo-hydro-mechanical couplings in fractured rocks.

Another marked effect is the variation of total stresses when porous deformation is restraint due to the existence of lateral constraints (e.g., inclusions, closed or compartmentalized reservoirs), or when the deformations are differential due to the existence of preferential flow paths (e.g., fault zones, high-transmissivity formations) (Rudnicki, 2011; Soltanzadeh and Hawkes, 2009). This poroelastic effect implies a nontrivial and often non-isotropic variation of the effective stress with direct consequences on deformations and failure (De Simone et al., 2017; Wu et al., 2021). In particular, the total stress changes along the longitudinal direction of fractures as a result of pressure changes, while the total stress in the transversal direction to the fracture experiences minimal total stress changes (Zareidarmiyan et al., 2018). Overall, fractured porous media entail a number of couplings between the hydraulic, thermal and mechanical fields that should be considered in numerical models in order to reproduce the phenomena (Figure 2.2).

2.2.2 Numerical coupling techniques

2.2.2.1 Fully coupled scheme

The fully coupled approach, also called monolithic, solves all the governing equations simultaneously, i.e., the hydraulic, mechanical, and thermal equations are solved at the same time at every time step. The solution is reliable and can be used as a benchmark for other coupling approaches. This method enjoys excellent stability properties and preserves first-order convergence of non-linear iterations, but it is computationally expensive and the code development may be harder compared to other methods (Dean et al., 2006; Phillips and Wheeler, 2007; Settari and Walters, 2001). Several simulators and codes use this type of coupling: DYNAFLOW (Prevost, 1993), CODE_BRIGHT (Olivella et al., 1996), KRATOS (Dadvand et al., 2010), DuMux (Flemisch et al., 2011), COMSOL Multiphysics, UDEC/3DEC (ITASCA), MOOSE (Gaston et al., 2009), OpenGeoSys (Wang and Kolditz, 2007), Irazu (Mahabadi et al., 2016), GEOS (Castelletto et al., 2019), PorePy (Keilegavlen et al., 2021a), and ResFrac (McClure et al., 2022).

2.2.2.2 Iteratively coupled scheme

This method, also called two-way coupling, uses a sequential approach, i.e., it first solves one problem (equation), whose solution then feeds the other governing equation(s) (Figure 2.3a). The results are then sent back to the first equation. These steps may be repeated in an iterative way. Therefore, several iterations might be necessary for each time step until all the equations reach convergence and provide the same solution as that of the fully coupled approach (Almani et al., 2023, 2016; Castelletto et al., 2015; Kim et al., 2011; Preisig and Prévost, 2011). The number of iterations may be large, such that the calculation time is similar to the fully coupled method. The advantage of this staggered treatment is that it allows coupling different simulators to solve each problem with the most appropriate one (Rutqvist, 2017). In addition, diverse domains for flow and mechanics can be used, reducing the computational time due to the fact that a small domain for flow can be chosen (Tran et al., 2005). Simulators using this type of coupling include TOUGH2-FLAC3D (Rutqvist et al., 2002), Stanford's General Purpose Research Simulator (GPRS) coupled with PyLith (Jha and Juanes, 2014), COMSOL Multiphysics, STARS (Bissell et al., 2011; CMG, 2003), VISAGE coupled iteratively with ECLIPSE (Ouellet et al., 2011; Stacey and Williams, 2017), and DYNAFLOW.

2.2.3 Explicitly coupled scheme

This method, also called one-way coupling, only transmits information unidirectionally within each time step, typically from the thermo-hydraulic problem to the mechanical one. This implies that pressure and temperature affect the effective stress field, causing deformation, but deformation does not change the hydraulic properties. This approach neglects to verify convergence following the solution of the ultimate equation. Accordingly, the method assumes that the outcome of the solution is accurate and proceeds to solve the next time step (Zienkiewicz et al., 1988). Examples of this type of coupling can be found in simulators like TOUGH2-FLAC3D, STARS, and DYNAFLOW, which allow selecting the coupling method. This is a straightforward technique, but the stability and the accuracy may be compromised if the time step is not adequately chosen (Preisig and Prévost, 2011).



Iteratively Coupled

Figure 2.3 Flowcharts of (a) iteratively and (b) explicitly coupled approaches

2.2.2.4 Loosely coupled

The method is similar to the explicit coupling, but the solutions of the flow and energy equations are only transferred to the mechanical equation after a number of time steps. The method is, therefore, computationally efficient but the intervals of coupling update have to be chosen in a reliable way (Gai et al., 2005). The VISAGE-FRONTSIM and the STOMP-ABACUS (Nguyen et al., 2016) simulators use this kind of coupling.

2.3 Representation approaches of fractured porous media

Fractures in rock formations, whether naturally occurring or induced through thermal or hydraulic means, represent separations or openings within geological structures that create discrete zones within the rock. The fundamental objective of characterizing fractures in reservoirs is to gain insight into the intricate behavior of heat, fluid flow, and transport within fractured rocks, as well as to quantitatively assess the impact of fracturematrix interaction on the overall flow patterns. A fracture can be defined as a narrow, deformable, high-permeability (compared to the rock matrix), and heterogeneous threedimensional zone, akin to a special porous medium sheet, surrounded by a stiff and lowpermeability, yet permeable, rock matrix. Fractures typically exhibit small apertures, supported by fillings or contacts, a consequence of the considerable in situ stress exerted on the rock matrix in deep reservoir formations. Hydraulic fractures, on the other hand, necessitate the support of proppants or sands to remain open and facilitate fluid flow.

Conceptualizing fractures as a distinctive porous medium naturally leads to the application of Darcy's law to quantify flow through fractures within reservoirs. This approach has been widely utilized in the literature and practical field applications for analyzing flow behavior in fractured porous media. However, it is essential to acknowledge that flow in fractured porous media entails greater complexity than that in purely porous media. The behavior of fracture flow is contingent upon the interplay with the surrounding matrix, and it is influenced by both the flow within the matrix and the spatial distribution and geometry of fractures and matrix components within the formation. Given the inherent uncertainties concerning in situ fractures' characteristics, including geometric properties and spatial distributions, various simple or simplified conceptual models and scenarios have been proposed, developed, and employed to approximate or characterize the intricate flow while considering the vital aspect of fracture-matrix interaction. This section presents a comprehensive overview of the commonly used conceptual models utilized for simulating coupled processes in fractured rocks.

There is not one model as a panacea and several approaches have been developed to adequately represent the mechanical, thermal, and hydraulic behavior of fractures. Traditionally, these methods have been generally classified into three main categories: continuum, discontinuum (discrete), and hybrid methods including a system of underlying methods carrying inherent advantages and disadvantages depending on the problem of interest (Berre et al., 2019; Lei et al., 2017; National Academies of Sciences, 2015; Viswanathan et al., 2022). It should be noted that the nomenclature adopted in the literature is often confusing. For instance, the term "discrete" is sometimes used to describe a continuum model with a singular representation of a fracture, and sometimes used to distinguish models with respect to fulfilling displacement compatibility between internal elements. Here, we adopt a classification based on the fracture representation.

2.3.1 Continuum approaches

The process of converting discrete fractures into a continuum representation, commonly referred to as upscaling, plays a significant role in constructing various continuum models that are specific to the type of fracture system being investigated. The choice of the upscaling approach is contingent upon the particular characteristics of the fractured medium and may involve the use of different techniques (Berkowitz, 2002; Berre et al., 2019; Flemisch et al., 2018; Renard and Ababou, 2022; Sævik et al., 2013; Wong et al., 2020). These methods present an evident preference in scenarios in which a continuum representation offers a more suitable approximation, such as when computational efficiency is of paramount importance, the fracture network exhibits a dense topology, and quantities of interest are averaged over extended time scales (Viswanathan et al., 2022).

2.3.1.1 Equivalent porous medium (single continuum model)

In the case of a sparsely connected fracture network, this modeling approach employing a single continuum representation, namely equivalent porous medium (EPM) (or Equivalent Continuum Models (ECM)) proposed by Snow (1969), may be employed. This method considers the concept of a representative elementary volume (REV), introduced by Bear (1972) (Figure 2.4). A heterogeneous medium would be divided into several REVs, and an average set of parameters would be assigned to each of them. Therefore, there is not an explicit representation of fractures and fractures are upscaled in conjunction with the matrix (Huang et al., 2017; Jiang et al., 2013; Liu et al., 2019). The method is adequate to reproduce flow and transport along fractures, particularly in solving large-scale water-yield problems (Doolin and Mauldon, 2001; Esposito et al., 2007; Scanlon et al., 2003). However, this technique is not able to simulate the mechanical behavior of fractures in a realistic way due to the fact that the jump in fracture displacements cannot be reproduced. The accuracy of this approach is still the topic of different investigations (Ma et al., 2023; Song et al., 2018; Zareidarmiyan et al., 2021).



Figure 2.4 Definition of porosity and representative elementary volume, adapted from Bear (1972)

2.3.1.2 Stochastic/heterogeneous continuum medium

The term "stochastic" pertains to the utilization of probability and statistical methods to account for uncertainty associated with the properties of fractured media (Ostoja-Starzewski, 2002; Vanderborght et al., 2006). Rather than assuming a deterministic distribution of fractures, the concept of stochastic continuum medium (SCM) encompasses the consideration of variability and randomness in fracture properties (Le Guennec et al., 2014; Öhman and Niemi, 2003; Tsang et al., 1996). These properties can include fracture orientation, aperture (size), spacing, and permeability. SCM approaches, which are typically used for inverse modeling rather than forward modeling, facilitate the generation of spatially variable representations of upscaled effective properties, acknowledging stochastic characteristics originating from the underlying fracture network. Incorporating stochastic methods, such as geostatistics, Monte Carlo simulation, or random field theory, enables the creation of multiple realizations of the subsurface model that account for the statistical attributes of fractures within the matrix. These realizations capture various possible configurations of fractures, resulting in a diverse array of flow and transport scenarios. The utilization of the SCM method proves particularly advantageous in situations where pertinent information concerning specific fracture locations is limited. The adoption of the stochastic continuum approach obviates the necessity for extensive information pertaining to fracture geometry or assumptions concerning the dominant influence of individual fractures on flow and transport processes. Instead, the method solely necessitates the delineation of a few dominant features, which can be effectively integrated into the stochastic continuum model as heterogeneous porous slabs (Ando et al., 2003; Neuman, 1988, 1987). In such cases, relying solely on a single realization of the random field may not accurately represent the intricacies of a particular field site. However, despite this limitation, the SCM method offers valuable insights by providing information regarding the anticipated ranges of bounding behavior.

2.3.1.3 Multi-continuum medium

2.3.1.3.1 Two-domain model (Dual-continuum model)

This concept encompasses two categories assuming either one (i.e., mobile-immobile model or double-porosity model) or two flow domains (i.e., mobile-mobile model or dualpermeability) (Figure 2.5). Reviews on two-domain models are given by (Gerke, 2006; Simunek et al., 2003). The idea of the double-porosity model (also known as mobileimmobile model (MIM)), introduced by (Barenblatt et al., 1960) and (Warren and Root, 1963), is based on the concept of dividing the porous medium into two distinct continua: a mobile region characterized by a high degree of connectivity between the pores and an immobile region characterized by a low degree of connectivity (Geiger et al., 2013; Yan et al., 2016; Zimmerman et al., 1993). Two distinct values of porosity are given for each system and flow is supposed to occur only through the fracture system while the matrix provides the storage capacity (Abushaikha and Gosselin, 2008; Chen and Teufel, 1997; Hosking et al., 2018; Xue et al., 2020; Zhao and Chen, 2006). This model treats matrix blocks as spatially distributed sinks or sources to the fracture system without accounting for global matrix-matrix flow. The interaction between both regions (fluid or heat exchange) is governed by the difference in pressures between the two systems in a "quasisteady" manner (Gelet et al., 2012; Hosking et al., 2020). Building upon the doubleporosity concept, some works have been carried out to explore the behavior of THM coupled processes in fractured media. Notably, (Bai and Roegiers, 1994) developed an early coupled THM constitutive model for double-porosity media, while (Masters et al., 2000) proposed a model assuming a single representative thermodynamics continuum encompassing heat conduction and convection. Conversely, (Zhang and Cui, 2011) devised a THM model that disregards the thermal impact on the hydraulic field. In contrast, (Khalili and Selvadurai, 2003) introduced a comprehensive, fully coupled THM constitutive model crafted systematically at a macroscopic scale. While predominantly grounded in the mechanics framework, some studies like (Gelet et al., 2012; K. Wang et al., 2023) contributed to a thermodynamics-based THM model.

Contrary to the double-porosity method, in dual-permeability models (mobile-mobile model), flow occurs not only in the fracture system but also within the matrix blocks and between them (Barenblatt et al., 1960; Dykhuizen, 1987; Moinfar et al., 2011; Šimůnek et al., 2003; Vogel et al., 2000). This modeling approach postulates the representation of the system as a composite of two overlapping interacting domains (Figure 2.5). One domain depicts an inter-aggregate fractured or meso-porous media, while the other domain represents an intra-aggregate meso-micro pore subsystem. The equations are solved simultaneously for both permeable and less permeable subsystems like porous media continuum models (Aguilar-López et al., 2020; Leij et al., 2012).



Figure 2.5 Schematic of dual-continuum models. In the double-porosity model, the flow domain of a naturally fractured medium is composed of low-permeability matrix blocks, embedded in a network of interconnected fractures. However, in the dual-permeability model, fractures and matrix are represented by separate grid blocks that are also connected to each other locally.

2.3.1.3.2 Triple-continuum model

In the dual-continuum approach, both the fracture and matrix systems are treated as locally uniform and homogeneous. An extension of the dual-continuum approach has been developed, known as the triple-continuum approach, to account for the influence of heterogeneity present in fractures or the rock matrix on flow within fractured porous media (Wang, 2005; Wu, 2016; Wu et al., 2004). This extended model encompasses rock matrix heterogeneity, the effect of small fractures, and fractured vuggy media (Abdassah and Ershaghi, 1986; Bai et al., 1993; Youssef and Alnuaim, 2017; Zhang et al., 2015). The utilization of triple-continuum models aims to address varying levels and scales of heterogeneity in the rock matrix or fractures. This is achieved by subdividing the rock matrix or fractures into two or more subdomains or continua, each characterized by distinct properties to represent the diverse flow behaviors within the fractured medium. In the triple-continuum model, the fracture-matrix system is conceptualized as consisting of a single porous-medium rock matrix and two types of fractures: large globally connected fractures, and small fractures that are locally connected to both the large fractures and the rock matrix. In essence, the triple-continuum method extends the dual-permeability approach by introducing an additional connection through the small fractures, which further interacts with the large fractures and the matrix blocks.

2.3.1.3.3 Multiple INteracting Continua (MINC)

The Multiple INteracting Continua (MINC) is a generalization of the dual-continuum model in order to handle non-isothermal and multi-phase flow. MINC is rigorous for handling transient flow between fractures and the matrix. In this method, each matrix block is discretized in a nested way in order to be able to reproduce the gradients (pressures, temperatures, capillary forces, or concentrations) in the matrix (Figure 2.6). Moving from the boundary to the center of the matrix block, different matrix regions are crossed, which are functions of the distance from the fractures and allow for a transient exchange between fractures and matrix. This transient regime enables the simulation of multi-phase and non-isothermal flow, coupling between fluid and heat flow, and variable compressibility (Bedoya-Gonzalez et al., 2023; Tatomir et al., 2011; Wang et al., 2017, 2014). The method was initially introduced by Pruess (Pruess, 1983; Pruess and Narasimhan, 1985; Wu and Pruess, 1988) for cubic matrix blocks but can be extended to irregular grids. Although the suitability of this technique has to be analyzed case-by-case, it has become a popular method and it is used by several simulators like STARS, TOUGH2 (Pruess, 1992) or Dumu^x (Flemisch et al., 2011).


Figure 2.6 Computational mesh in the MINC approach

2.3.2 Discrete approaches

The explicit or discrete-fracture modeling approach is characterized by the inclusion of every individual fracture within the model domain, explicitly describing the flow through each fracture. This modeling approach represents a rigorous method in contrast to continuum approaches. However, its practical application in field-scale modeling studies presents significant challenges, stemming from demanding data requirements and computational intensity. The large number of fractures typically encountered in field simulations makes their comprehensive inclusion impractical. Additionally, this approach necessitates a detailed understanding of the geometric properties of fractures and the matrix, as well as their spatial distributions, which are rarely available for natural fractures at field sites. The complexity of the explicit modeling approach escalates when addressing multi-phase flow and thermal processes within intricate fracture-matrix systems observed in actual reservoirs. Consequently, the explicit-fracture modeling approach had limited utility in field-scale studies until approximately a decade ago. Nevertheless, recent advances have led to the increasing popularity and extensive adoption of the discrete-fracture model in various geo-engineering applications.

2.3.2.1 Channel/pipe network (C/PN)

This model explicates the fact that fracture distribution and aperture heterogeneity give rise to preferential pathways (Larsson et al., 2012; Tsang and Neretnieks, 1998; Tsang and Tsang, 1987), creating a network of interconnected channels or pipe elements, where each channel or pipe represents an individual fracture or a set of fractures (Gylling et al., 1999; Khademi et al., 1999; Moreno and Neretnieks, 1993). These channels or pipes characterized by their hydraulic and mechanical properties are connected by nodes, which correspond to the intersections or junctions of fractures within the system (Tsang et al., 1988). It is conventionally assumed that these channels or pipes have a constant crosssectional area and are often approximated as circular or rectangular in shape. While fluid flow and heat transfer equations are solved within these channels or pipes, the deformation and fracture propagation are modeled in the surrounding rock mass using continuum mechanics. To simulate fluid flow through a fractured medium using a channel/pipe network approach, the network is discretized into a set of equations describing the flow through each channel or pipe, as well as the flow through the connecting nodes. Subsequently, this system of equations is numerically solved to obtain the pressure and flow rate at each point in the network (Y. Chen et al., 2018; Fernández-Pato and García-Navarro, 2014). The flow equations in the C/PN model are locally one-dimensional and can be analytically solved in the Laplace domain, and in some cases, even in the time domain (Moreno and Neretnieks, 1993; Sharma et al., 2023). Additionally, transport in the channels (in-fracture advective transport) is modeled via particle tracking methods, while the interaction with the rock matrix (diffusion, absorption, etc.) can be included in the particle tracking formulation in the form of analytical solutions (Liu et al., 2018; Mahmoudzadeh et al., 2013; Neretnieks, 2006; Shahkarami et al., 2016), which obviates the need for numerical discretization of the domain and allows for a more direct focus on the network structure and connectivity to reproduce field data (Dessirier et al., 2018; Li et al., 2014). Some C/PN frameworks utilize full lattices of channels and stereological arguments to infer lattice spacing and flow-wetted surfaces from observations along borehole sections. These derived parameters are then employed to calculate flow and transport through the system. C/PN models have the advantage of being computationally efficient due to a significant reduction in the number of degrees of freedom in the solution matrix. They are relatively simple to set up and can handle large and complex fracture networks. They are also flexible, allowing for the inclusion of additional processes such as two-phase flow or geomechanical deformation (Dessirier et al., 2023; Junqi et al., 2022; Shahkarami et al., 2019). However, they are limited by their assumption of steady-state flow and their inability to capture spatial variations in permeability or other properties of the fractures. Diverse adaptations of C/PN models have garnered considerable attention for the representation of deep crystalline rock systems characterized by low overall hydraulic conductivity. Among these adaptations is the sparse channel network, featuring sparsely populated lattice networks. This configuration comprises a limited number of elongated channels, which are notably spaced far apart, yet retaining the ability to interact at their intersections (Black et al., 2017; Black and Barker, 2018; Dessirier et al., 2018). Notably, it is pertinent to highlight that the conventional regular lattice arrangement is not a prerequisite for the utilization of the underlying analytical solutions governing channel flow and transport. For an in-depth review of the applications of sparse channel network models, interested readers are directed to the work by (Figueiredo et al., 2016).

2.3.2.2 Discrete fracture network (DFN)

The Discrete Fracture Network (DFN) is a method suitable for the modeling of flow and transport processes through a connected large-scale fracture network (Baisch et al., 2010; Bruel, 2007; Li et al., 2020; McClure and Horne, 2011). In this approach, the reservoir is treated as a combination of distinct, individual fractures and an impermeable rock matrix, and all fluid is assumed to reside within the fracture network (Figure 2.7). DFN models are especially suitable for porous media where the complete porosity and permeability can be attributed to fractures that can be explicitly represented. The model is also commonly employed as a means to model fractures in low-permeable porous media in a generalized context.



Figure 2.7 Stochastically generated Discrete Fracture Network (DFN) with 5033 fractures in a 109 m³ domain. Each fracture is shown in a distinct color. DFN parameters represent the natural repository site Forsmark, Sweden (Makedonska et al., 2015).

DFN models exhibit an advantageous capability of effectively capturing the distinct effects of fractures, albeit at the cost of higher computational intensity compared to continuum models. Notably, this approach encounters challenges due to the inherent heterogeneous structure of fractured rock (de Dreuzy et al., 2012; Li et al., 2021), particularly when dealing with the leaky nature of fractures in high-pressure injections and temporal scales that demand consideration of matrix diffusion. Moreover, the presence of fractures of varying sizes, locations, and orientations necessitates the explicit representation of a significant number of fractures, which inevitably impacts the computational efficiency of the model. Additionally, due to practical limitations, it becomes unfeasible to include all contributing fractures to the flow within the model, further introducing complexities and uncertainties (Fadakar Alghalandis, 2017; Jing and Stephansson, 2007a).

The main characteristics of DFN are the geometry of the fracture system and the transmissivity of the fractures. Nevertheless, these features are generally unknown, because of the lack of information. Hence, to overcome these problems, the fracture geometry is often stochastically generated based on the statistical distributions of fracture parameters which are assumed or inferred from borehole and outcrop observations (Afshari Moein et al., 2018; Bour et al., 2002; Darcel et al., 2003; Hyman et al., 2015; Lei and Wang, 2016; Ringel et al., 2022, 2019; Somogyvári et al., 2017; Xu and Dowd, 2010). Similar to CP/N models, advective transport through the system of connected fractures is usually solved via particle tracking, while diffusive exchange between the fluid in the fractures and the rock matrix is solved analytically (Cvetkovic et al., 1999; De Simone et al., 2023a; Hyman et al., 2019). Besides flow and transport, many conventional DFN models do not incorporate mechanical processes, because they mostly occur in the rock matrix which is not represented. Simplified formulations including the semi-analytical estimation of thermal rock deformation and consequent fracture aperture variation have been recently proposed, e.g., (De Simone et al., 2021). Some recent advances have been made to consider the effects of matrix in THM processes. For exaple, DFN modeling has been employed to provide a hydro-mechanical characterization of anisotropic fractured rock masses (Davy et al., 2018; De Simone et al., 2023b; Gottron and Henk, 2021) and to simulate THMC properties/responses of fractured porous media (Lei et al., 2021, 2020; Lei and Gao, 2018), making this method to be not only applicable for densely but also sparsely fractured scenarios. Recently, (Hadgu et al., 2017) carried out a comparative study of DFN and ECM models for simulating flow and transport and their results showed that both methods can be used to model the far field of a nuclear waste repository in crystalline rock.

In contrast to the CP/N method, DFN models necessitate substantial computational resources to adequately discretize each fracture plane within the entire network system,

considering the potential incorporation of variable aperture and transmissivity across these fracture planes. It is important to highlight that contemporary advances in DFN modeling have sought to streamline complex fracture networks into configurations resembling channel networks through the application of graph theory and topological analysis (Berrone et al., 2020; Doolaeghe et al., 2020; Hyman et al., 2018; Osthus et al., 2020). (Lei et al., 2017) presented a discussion of the state-of-the-art on the use of DFN for modeling geometrical characteristics, geomechanical evolution, and hydromechanical behavior of fractured rocks.

2.3.2.3 Discrete fracture-matrix (DFM)

The Discrete Fracture-Matrix (DFM) method aims to resolve the trade-off between reduced precision resulting from upscaling of fractures and increased geometric complexity from representing fractures explicitly (Bogdanov et al., 2003; Matthäi et al., 2007; Matthäi and Belayneh, 2004; Monteagudo and Firoozabadi, 2004; Mourzenko et al., 2004; Noorishad and Mehran, 1982; Painter et al., 2002). By localizing the fluid within explicitly represented fractures and the interstitial porous matrix, this approach allows for the assimilation of fractures with lengths significantly smaller than the domain size into the matrix domain, thereby contributing to secondary permeability without being explicitly characterized by the fracture network (Wang and Lei, 2021). Consequently, the DFM technique effectively handles fractures in permeable media that necessitate explicit representation due to their significant and dominant influence on processes. While the fundamental framework of DFM models for flow dates back several decades (first introduced by (Baca et al., 1984; Noorishad and Mehran, 1982)), their development for at-scale applications is relatively recent compared to other computational models discussed in the literature (Jiang and Younis, 2017; Nick and Matthäi, 2011).

DFM models allow for a thorough investigation of processes occurring at the interface between fractures and the rock, such as capillary pressures in two-phase flow (Aghili et al., 2019) and the hydro-mechanical interaction between flow and the host medium (Garipov et al., 2016). The resolution of this interface in DFM models offers a detailed representation of these processes. However, this formulation poses numerous challenges concerning computational geometry and mesh generation, as well as numerical schemes for THM processes. Multi-dimensional computational meshes (3D volumes and 2D fracture planes) are inherent to DFM models, necessitating the development of novel numerical methods and ensuring the preservation of conservation laws. Existing DFM models can be broadly categorized into two classes based on how they address the first issue, which subsequently dictates their approach to the second issue. DFM models either employ a mesh representation of the matrix that aligns or coincides with the mesh of the fracture network, referred to as the conforming mesh method (Ahmed et al., 2017; Karimi-Fard et al., 2004), or they do not, known as the non-conforming mesh method (Berrone et al., 2017; Boon et al., 2018; Flemisch et al., 2016; Schwenck et al., 2015). Presently, most DFM models for THM coupled processes in fractured media are either 2D, quasi-2D, or limited to relatively simple 3D geometries, owing to the method's relative infancy and computational constraints (Aghili et al., 2019; Hægland et al., 2009; Jiang and Younis, 2015; Sandve et al., 2012). However, for flow modeling, recent studies have considered rather complex 3D geometries (Hyman et al., 2022; Keilegavlen et al., 2021b; Stefansson et al., 2021; Wang et al., 2022). (Berre et al., 2021) and (Flemisch et al., 2018) have presented benchmark cases and various numerical schemes currently in use for DFM models and investigated the capabilities of DFM methods in handling complexities common to fracture networks. A detailed review on DFM methods can be found in (Berre et al., 2019).

2.3.3 Hybrid approaches

In practice, the combination of continuum methods and discrete methods is being increasingly employed to represent fractured porous media. These methods, known as hybrid methods, involve various combinations of continuum and DFM approaches (Wong et al., 2020). Theoretically, all fractures within the whole system could be integrated into the fracture domain. However, due to computational complexity, the explicit representation of all fractures is not practical. This issue can be overcome by the combination of DFM models with continuum methods, which provides computational efficiency (Figure 2.8). Hybrid methods offer a flexible and effective approach for modeling flow and transport in permeable rocks, accommodating the advantages of both continuum and DFM methods.

The more complex the hybrid model is, the higher the accuracy as well as the computational cost. Thus, a trade-off between accuracy and computational time should be reached. In cases where fracture network properties exhibit heterogeneity across different zones, it may be necessary to apply distinct hybrid models in each zone to optimize computational efficiency. This shift towards hybrid models has been motivated by the observation that fractured reservoirs exhibit multiple length scales, leading to potential errors in upscaling on a grid cell basis. A full representation of the fracture network via DFM methods would ideally overcome such errors. However, due to

computational limitations, continuum methods must often be employed in conjunction with DFM methods.



Figure 2.8 Schematic illustration of the hybrid modeling approach where large-scale fractures are modeled by a DFM model and a continuum approach is used to capture the dense small-scale fractures and vugs.

2.3.3.1 Single-porosity hybrid model

This model utilizes a single continuum to represent the matrix and small-scale fractures, known as the pseudo-matrix, while explicitly accounting for larger fractures (Arbogast, 1992; Lee et al., 2001; Li and Lee, 2008; Rogers et al., 2007; Siripatrachai et al., 2016). Consequently, it can be viewed as a streamlined version of the more complex DFM model, offering a reduction in model complexity without compromising the accuracy. Within the larger framework of hybrid models, the single-porosity hybrid model is recognized as the most straightforward hybrid model available.

The advantages of this method include its ability to capture the effects of both advection and diffusion in the porous medium, and its ability to accurately predict transport behavior for a wide range of flow and transport conditions. Additionally, the model is relatively easy to implement and computationally efficient. One major limitation is that it assumes a constant immobile porosity, which may not be accurate in all cases. Additionally, the model does not account for the effects of spatial heterogeneity, which can significantly impact transport behavior in porous media. Finally, the model may not accurately capture transport behavior in cases where the immobile phase plays a significant role in transport, such as in some multi-phase flow systems.

2.3.3.2 Challenges in hybrid models

The emergence of hybrid methods represents a promising development in the field of geomechanics, flow, and transport modeling in fractured media. However, their implementation raises several questions regarding their construction. Notably, the issue of which fractures should be upscaled and which should be explicitly modeled is a significant concern. Furthermore, determining how many continua should be used to represent upscaled fractures and which continuum each fracture should belong to presents an additional challenge. The resolution of these questions may be zone-dependent, considering the possibility of spatial variations in fracture network properties within a reservoir. The determination of optimal hybrid method construction and implementation strategies represents a critical area for future research.

The process of determining which fractures to allocate to the fracture domain or matrix domain lacks a well-established methodology. Typically, the selection is made based on fracture lengths (Lee et al., 2001; Liu et al., 2021; Wang and Lei, 2021; Wong et al., 2020; Zhang et al., 2020). However, more advanced and application-specific selection criteria may be employed, such as fracture connectivity and the volume of host material, where fractures represent the main conduit for the global flow field. The method of upscaling representation may also be tailored to suit the specific application; while the traditional approach has been a single-continuum method, as detailed by (Karimi-Fard et al., 2004), multi-continuum approaches have also been applied, as demonstrated by (Jiang and Younis, 2017).

2.4 Theoretical formulations for modeling THM processes

2.4.1 Balance laws in the rock matrix

THM coupling models have been formulated based on two fundamental partialcoupling mechanisms firmly established in the framework of continuum mechanics. The first mechanism is the thermo-elasticity of solids describing the interaction between the stress/strain and temperature fields through thermal stress and thermal expansion. The second is poroelasticity theory accounting for the interplay between pore fluid effects and macroscopic deformation in porous media. These mechanisms are grounded in classical physical laws such as Hooke's law of elasticity, Darcy's law of flow in porous media, and Fourier's law of heat conduction. The derivation of the equations of poroelasticity and thermoelasticity couplings is given by (Coussy, 2004; Noorishad and Tsang, 1996; Stephansson et al., 1997; Tsang, 1999; Zimmerman, 2000). These equations are closely analogous to one another and within the framework of this analogy, the temperature and the pore pressure play similar roles. The THM coupling effects are expressed as three interrelated partial differential equations (PDEs) to conserve mass, energy, and momentum, which describe the interactions among fluid flow, heat transfer, and solid deformation processes. The fluid balance equation describes the conservation of mass and the flow of fluids through the fractured media, including the interconnections between fractures and the surrounding matrix. The momentum balance equation governs the forces that influence fluid flow, including pressure gradients, fluid viscosity, and mechanical deformation. The energy balance equation describes the temperature and pressure of the subsurface system. Here, we adopt geomechanics sign convection in which compression is positive.

2.4.1.1 Fluid mass balance

The mass balance of fluid in a porous medium accounting for Darcy's law and the advection provoked by solid motion can be expressed by the continuity equation (Bear, 1972) as

$$\rho_f \alpha_B \frac{\partial \varepsilon_v}{\partial t} + \rho_f S \frac{\partial p}{\partial t} + \phi \alpha_T \frac{\partial T}{\partial t} + \nabla \cdot \left(\rho_f \mathbf{q}\right) = f_w, \qquad (2.2)$$

$$\mathbf{q} = -\frac{k}{\mu} (\nabla p + \rho_f g \nabla z), \qquad (2.3)$$

$$S = \frac{\phi}{K_f} + (\alpha_B - \phi) \frac{1 - \alpha_B}{K_d}, \qquad (2.4)$$

where ρ_{t} and μ are the fluid density and dynamic viscosity, respectively, which are functions of pressure and temperature, a_{i} is the Biot–Willis coefficient, ε_{i} is the rock matrix volumetric strain, t is time, S is the storage coefficient, p is fluid pressure, ϕ [-] is the porosity, a_{τ} is the linear thermal expansion coefficient, T is temperature, q is the Darcy velocity, f_{ε} is the source/sink term of fluid (representing fluid influx or outflux from the rock element), k is the intrinsic permeability, g is the acceleration of gravity, z is the elevation from a reference plane, K_{t} is fluid bulk modulus, and K_{d} is the drained bulk modulus of the rock. The first three terms on the left side of Eq. (2.2) describe the changes in rock matrix volume due to strain, pressure, and temperature, and the last term gives the liquid flow due to pressure gradient and gravity according to Darcy's Law.

2.4.1.2 Momentum balance

Neglecting the inertial term, that is, under a quasi-static condition, the momentum balance reduces to the equilibrium equation of stresses (Biot, 1956; McTigue, 1986)

$$\nabla \cdot \boldsymbol{\sigma} + \boldsymbol{b} = \boldsymbol{0}, \tag{2.5}$$

where $\boldsymbol{\sigma}$ is the total stress tensor and b is the vector of body forces. The relationship between stress tensor $\boldsymbol{\sigma}$, strain tensor $\boldsymbol{\varepsilon}$, and fluid pressure p is

$$\boldsymbol{\sigma} = \mathbf{C}(\varepsilon - \varepsilon_T) - \alpha_B p \mathbf{I}, \tag{2.6}$$

$$\varepsilon_T = \alpha_T (T - T_0), \tag{2.7}$$

where C is the constitutive matrix, ε_T is the thermal strain, I is the identity matrix, and T_0 is the reference temperature. According to Biot's theory (Biot, 1962), the fluid pore pressure is proportional to the dilation of the porous matrix and the variation of fluid content (ξ_v)

$$p = B(\xi_v - \alpha_B \varepsilon_v), \tag{2.8}$$

where B is the Biot modulus, which is the inverse of the storage coefficient.

2.4.1.3 Energy balance

Energy balance is given by the convection–diffusion equation (Nield and Bejan, 2017), which reads

$$(\rho H)_{eff} \frac{\partial T}{\partial t} + \rho_f H_f \mathbf{q} \cdot \nabla T - \nabla \cdot (\kappa_{eff} \nabla T) = f_h, \qquad (2.9)$$

$$(\rho H)_{eff} = (1 - \phi)\rho_r H_r + \phi \rho_f H_f, \qquad (2.10)$$

$$\kappa_{eff} = (1 - \phi)\kappa_r + \phi\kappa_f, \qquad (2.11)$$

where H is the specific heat capacity, κ is the thermal conductivity (Huber et al., 2012), and f_h is an external/internal supply of energy. The subscripts "f", "r", and "eff" represent fluid, rock matrix, and effective value, respectively. Note that the thermodynamic properties are volumetrically averaged (weighted arithmetic mean) to account for solid matrix and pore fluid as the effective values (Eqs. 2.10 and 2.11). The first term on the left-hand side of Eq. (2.9) is the change in energy, the second term describes the convective energy due to heat carried by the moving liquid, and the third term represents the temperature conduction in the liquid-filled rock matrix.

2.4.2 Balance laws of fractures

Within the framework of continuum mechanics, rock fractures can be characterized by a dual set of surfaces, accommodating both normal and shear displacements. The fluid dynamics occurring within these fractures are expounded through the integration of the continuity equation and a tangential adaptation of Darcy's law, specifically tailored to the distinctive attributes of fracture elements

$$\rho_f S_{fr} b_{fr} \frac{\partial p}{\partial t} - \nabla_{fr} (\rho_f \mathbf{q}_{fr}) = b_{fr} f_{w}, \qquad (2.12)$$

$$\mathbf{q}_{fr} = -\frac{k_{fr}}{\mu} b_{fr} (\nabla_{fr} p + \rho_{fr} g \nabla_{fr} z), \qquad (2.13)$$

where S_{fr} is the storage coefficient of fractures, k_{fr} is the fracture element's permeability, b_{fr} is the aperture of the fracture element, \mathbf{q}_{fr} is the flow velocity in the fracture (the volumetric flow rate per unit length in the fracture element), and ∇_{fr} denotes the gradient operator restricted to the fracture element's tangential plane. When void fluid-filled fractures are assumed, it is widely accepted that the storage term (first term of Eq. (2.12)) is equal to the temporal variation of the fracture aperture and that k_{fr} is proportional to the square of the fracture aperture according to the cubic law. In doing these assumptions, the distinction between hydraulic aperture and true (mechanical) aperture is ignored (Renshaw, 1995). Similarly, heat transfer in fracture elements can be expressed as

$$b_{fr}(\rho H)_{eff}\frac{\partial T}{\partial t} + b_{fr}\rho_f H_f \mathbf{q}_{fr} \cdot \nabla_{fr} T - \nabla_{fr} \cdot (b_{fr}k_{eff}\nabla_{fr} T) = b_{fr}f_h, \qquad (2.14)$$

2.4.3 Fractured media constitutive models

The present work does not strive to provide an exhaustive review of all the available rock and joint constitutive models. Interested readers are advised to refer to (Barton et al., 1985; Jaeger et al., 2009; Jing and Stephansson, 2007b; Lei and Barton, 2022; Yan et al., 2020). Instead, we briefly introduce the main categories of various constitutive models.

The classical constitutive models are predominantly grounded in the principles of elasticity and plasticity. Linear thermoporoelasticity has emerged as the prevalent assumption to model the behavior of rocks. When adopting the CHILE (Continuous, Homogeneous, Isotropic, Linear Elastic) hypothesis, the constitutive law can be expressed through two distinct material properties (Jing, 2003). These can either be represented by the widely recognized Young's modulus and Poisson's ratio, or by Lame's two parameters, signifying their independence. Consequently, changes in stresses are a function of changes in strain, pressure, and temperature (Biot, 1956; McTigue, 1986) and Eq. (2.6) turns to

$$\Delta \boldsymbol{\sigma} = K \varepsilon_{v} \mathbf{I} + 2G \left(\Delta \boldsymbol{\varepsilon} - \frac{\varepsilon_{v}}{3} \mathbf{I} + \frac{\alpha_{b}}{2G} \Delta p \mathbf{I} + \frac{3K}{2G} \alpha_{T} \Delta T \mathbf{I} \right).$$
(2.15)

Conversely, elastic strain tensor $\pmb{\epsilon}$ can be expressed with the total stress, pressure, and temperature as

$$\boldsymbol{\varepsilon} = \frac{1+\nu}{E}\boldsymbol{\sigma} - \frac{3\nu}{E}\sigma_m \mathbf{I} - \frac{1-2\nu}{E}(\alpha \Delta p \mathbf{I}) - \Delta T \alpha_T \mathbf{I}, \qquad (2.15)$$

where $\sigma_m = \frac{tr(\sigma)}{3}$ is the mean total stress, $K = \frac{E}{3(1-2\nu)}$ is the bulk modulus, $G = \frac{E}{2(1+\nu)}$ is the shear modulus, E is Young's modulus, ν is the Poisson ratio. The effective stress tensor is $\sigma' = \sigma - \alpha_B p \mathbf{I}$.

More complex anisotropic elastic models can be formulated through closed-form derivations by exploring alternative elastic symmetry conditions for intact rocks (Dutler et al., 2018; Noorian Bidgoli and Jing, 2014; Yang et al., 2014). This includes transversely isotropic elasticity, as well as models for a continuum of fractured rocks intersected orthogonally by either infinitely large or finite-sized fractures. Such approaches enable the development of equivalent or effective elastic properties for fractured media, leading to more sophisticated constitutive models of anisotropic elasticity (Murakami and Hegemier, 1989; Singh, 2000; Wu and Wang, 2001).

Plastic and elastoplastic models have been developed and extensively employed for fractured rocks since the 1970s, established primarily on the foundations of the classical theory of plasticity, with Mohr-Coulomb (linear) and Hoek-Brown (non-linear) failure criteria serving as common yield functions and plastic potentials in typical models (Hoek, 1983; Hoek and Brown, 1997; Rafiei Renani and Cai, 2022). Moreover, two fundamental features of the plastic behavior of fractured rock are strain-softening and strain-hardening, with the former being more frequently observed in the context of uniaxial compression testing (Desai and Salami, 1987; Du et al., 2015; Read and Hegemier, 1984; Shen et al., 2019; Zhang et al., 2021; Zienkiewicz and Mroz, 1984). Strain localization closely linked to the constitutive models is another deformational phenomenon in fractured rocks and has been the subject of study through the use of plasticity and damage mechanics models (Agard et al., 2011; Fossen et al., 2007; Gardner et al., 2017; Pardoen et al., 2015; Rattez et al., 2018; Zhang et al., 2013).

Incorporating failure criteria is an integral aspect of the constitutive modeling of rocks, as they serve as yield surfaces or plastic potential functions in plasticity models. While the Mohr-Coulomb and Hoek-Brown criteria are widely used, various failure criteria have been suggested for rock masses over the years (Bahrami et al., 2017; Das and Basudhar, 2009; González Nicieza et al., 2006; Jaiswal and Shrivastva, 2012; Labuz et al., 2018; Lee et al., 2012).

The effect of viscosity has been considered in constitutive modeling in combination with other basic deformation mechanisms (elasticity and plasticity) leading to constitutive models with visco- prefixes. Two mechanisms account for the effect of viscosity: creep and relaxation. Creep pertains to the phenomenon of increasing deformation (strain) under constant loading (stress), while relaxation pertains to decreasing loading (stress) while the deformation (strain) remains constant (Borja et al., 2020; de Borst and Duretz, 2020; Farhat et al., 2017; Fossum and Brannon, 2006; Maranini and Yamaguchi, 2001; Souley et al., 2011; H. Zhou et al., 2008).

Constitutive models for rocks have been also developed utilizing continuum damage mechanics principles (Kachanov, 1958). These models incorporate either isotropic damage. which uses a scalar representation (Oliver, 2000; Saksala et al., 2015), or anisotropic damage, using a tensor representation (Fernández and Ayala, 2004; Olsen-Kettle and Sarout, 2022) of the void formation, micro-cracking, or embedded fracture phenomena that occur in the rock under loading. This theory has a close relationship with both continuum mechanics and fracture mechanics, providing a bridge between these two. The formulation of the damage mechanics models exhibits certain parallels with plasticity models, such as the use of damage evolution laws instead of flow rules. However, unlike plasticity theory, damage mechanics principles are not subject to the restriction of the normality rule. Additionally, damage mechanics theory has distinct advantages in simulating strain-localization factors using continuum approaches and in studying the brittle-ductile deformation model transitions that are observed during rock sample testing (Chen and Qiao, 2018; de Borst, 2002; Liu and Yuan, 2015; Liu and Zhang, 2015; Liu et al., 2015; Oliver et al., 2002; Xie et al., 2020a, 2020b). Generally, the utilization of a damage mechanics model is deemed more pertinent for materials exhibiting brittle or semibrittle characteristics, while the employment of a plasticity model is perceived as more appropriate for the analysis of ductile materials. Nevertheless, it should be noted that the incorporation of softening within the plasticity framework can, to some extent, accommodate the representation of brittle behavior (Wang and Lei, 2023).

2.4.4 Fracture constitutive models

Fracture constitutive models have been formulated either through empirical or theoretical approaches. In general, within the matrix, displacement, pressure, and temperature are recognized as the primary variables, while, for fractures, the primary variables predominantly consist of contact tractions (including both normal and shear components), pressure, and temperature, whereas fluxes and displacements assume roles as variables along the interfaces that bridge the fracture and matrix. When implementing fracture constitutive models into continuum numerical methods (via interface elements), numerical instabilities may arise due to the zero-thickness of interface elements. In contrast, the implementation of these models into discontinuum methods is generally simpler due to the use of contact mechanics principles. However, inter-penetration of solid blocks must be prevented through the use of techniques like penalty function, Lagrangian multipliers techniques, or regularization scheme (Abedi and Clarke, 2019; Hou et al., 2023; Jones and Papadopoulos, 2000; Lei et al., 2016; Salimzadeh et al., 2018; Stefansson et al., 2021).

2.4.4.1 Quasi-static constitutive models

A number of constitutive models have been developed to characterize the mechanical behavior of rock fractures under quasi-static loadings through empirical approaches. Among them, Goodman's model stands out for its treatment of nonlinear fracture deformation characteristics (Goodman et al., 1968), while the Barton-Bandis model is renowned for its ability to capture the coupled hydro-mechanical response and to consider non-linear normal/shear behavior of fractures examined against extensive experimental data (Bandis et al., 1983; Barton et al., 1985; Lei and Barton, 2022). These empirical models offer valuable insights into fracture behavior and are frequently used in rock engineering practice due to their typically simpler mathematical forms and reduced number of parameters required, particularly in cases where simple loading mechanisms are anticipated. Yet, their potential violation of the second law of thermodynamics in complex stress-displacement scenarios raises concerns. Furthermore, their applicability outside of their original databases remains uncertain, necessitating the development of robust validation techniques and the incorporation of a thermodynamic framework. Improved attention to these factors will bolster the reliability and wider applicability of these models in practical rock engineering contexts (Asadollahi and Tonon, 2010; Babanouri and Fattahi, 2018; Chen et al., 2023, 2020; Grasselli and Egger, 2003; Jing and Stephansson, 2007c; Lei et al., 2016; Lei and Barton, 2022; Lin et al., 2019).

The development of theoretical models for rock fractures is typically grounded in the principles of solid mechanics, specifically in plasticity or contact mechanics. In contrast to empirical models, theoretical models must adhere strictly to thermodynamic principles, thus establishing a more rigorous foundation in rock mechanics. However, this theoretical correctness comes at the cost of typically more complex mathematical forms and an increased number of parameters (like (Amadei and Saeb, 1990; Souley et al., 1995)), which in turn requires additional considerations and costs for parameterization when implementing such models. The most common constitutive models for rock fractures developed via the theoretical approach are formulated using principles of plasticity theory. These models leverage the similarity between the plastic hardening-softening deformation of solids and the shear stress (traction)-shear displacement components of rock fractures (Desai and Fishman, 1991; Lee and Cho, 2002; Nguyen and Selvadurai, 1998; Oliveira and Lourenço, 2004; Plesha, 1987; Xie et al., 2022a, 2022b).

2.4.4.2 Dynamic constitutive models

To properly replicate the transient slip resulting from shear failure of pre-existing fractures, it is imperative to employ a suitable dynamic constitutive law, in addition to representing the fracture as a discontinuity plane. The determination of shear resistance in pre-existing fractures can be approached through the application of static friction coefficient (μ_s) in accordance with the Mohr-Coulomb theory. Additionally, in scenarios where the deformation of fractures is influenced by frictional resistance, it becomes necessary to define a dynamic friction coefficient (μ_d). Empirical evidence from experiments has motivated the development of four common friction models for fracture surfaces (Daub and Carlson, 2010):

• Stress-weakening/strengthening model

This model operates by instantaneously reducing the coefficient of friction to a new dynamic value (μ_d) when the shear stress of a fracture surpasses the Mohr-Coulomb failure criterion determined by the static friction coefficient (μ_s). This model is also referred to as the velocity-weakening model due to the decrease in shear strength with increased slip velocity. It provides a simplistic representation of the failure

behavior of fracture surfaces subjected to a sudden increase in slip velocity (Dieterich, 1979). Notably, this friction model is classified as "inherently discrete" since the strength of the failing elements experiences a discontinuous drop during the slip (Ben-Zion and Rice, 1993; Rice, 1993). While the model lacks convergence properties, it has been observed to yield qualitatively acceptable results (McClure and Horne, 2011).

- Slip-weakening/strengthening model
 - In slip-weakening models, the frictional resistance between two surfaces decreases as the slip or relative displacement between the two surfaces increases. This implies that the fracture becomes weaker as it slips. Slip-weakening is commonly associated with dynamic rupture processes during seismic events, where the fault initially experiences high frictional resistance but gradually weakens as slip occurs, allowing the fault to slide more easily (e.g., (Boyet et al., 2023)). In the slip-weakening model, the friction of fracture surfaces diminishes from a static value (μ_s) to a dynamic value (μ_d) as slip progresses over a critical distance (d_c) (Andrews, 2005, 1985; Bizzarri, 2012; Borja and Foster, 2007; Ikari et al., 2013). Slip-strengthening, on the other hand, refers to the phenomenon where the frictional resistance between two surfaces increases as the slip or relative displacement between them increases. Slip-strengthening can be associated with certain geological conditions where the fault becomes more resistant to sliding as it slips, potentially leading to more significant stress accumulation and higher levels of ground shaking during a seismic event (Suzuki and Yamashita, 2008, 2007; Ujiie et al., 2009; Yuan and Prakash, 2012).
- Time-weakening model

It is similar to the slip-weakening friction model with the only difference of a required threshold, the critical time t_c , for friction to decrease from a static to a dynamic value (Andrews, 2004; Hatano, 2009; Hu et al., 2017).

• Rate- and state-dependent friction model

This model arose from observing the results of some experiments (Dieterich, 1979, 1978; Ruina, 1983), where variations in the value of friction coefficient were noticed. It enables the simulation of fault slip, while also reproducing fast and inertially limited slip (Segall, 2010), a characteristic of earthquakes. Based on the evolution of the slip rate (or velocity) and the state variable, which induces changes in the friction coefficient value, rate and state friction models offer an effective means of modeling this phenomenon. In contrast to the previous friction models, this friction

model can capture the healing (strengthening mechanisms) of friction after a high-velocity slip, which is essential for earthquake modeling if both seismic and aseismic slip should be captured (Scholz, 1998). This constitutive law, which does not suffer from convergence issues, has become very popular due to its capacity of reproducing seismic slip and it is widely used to this end (Cueto-Felgueroso et al., 2017; Jha and Juanes, 2014; McClure and Horne, 2011).

2.4.5 Permeability evolution

Porous media encompass both solid (V_s) and pores (V_p) . The summation of these constituent volumes coalesces to define the overall bulk volume of the composite system $(V=V_s+V_p)$. Therefore, the evolution of the porosity can be described as

$$d\phi = d\left(\frac{V_p}{V}\right) = (1 - \phi)\frac{dV}{V} - (1 - \phi)\frac{dV_s}{V_s},$$
(2.17)

where $\varepsilon_v = \frac{dv}{v}$ is the volumetric strain of the porous medium, and $\frac{dv_s}{v_s}$ is the volumetric strain of the solid matrix as

$$\frac{dV_s}{V_s} = -\frac{1}{K_s}dp + \alpha_T dT.$$
(2.18)

Subsequently, Eq. (2.17) yields

$$\phi = 1 - (1 - \phi_0) \exp\left[\frac{-(p - p_0)}{K_s + \alpha_T (T - T_0) - (\varepsilon_v - \varepsilon_{v0})}\right],$$
(2.19)

where the subscript 0 indicates the reference value of the variable.

Initially, if fractures are closed, fluid flows through the matrix. Changes in matrix permeability can be estimated with Kozeny's model based on the evolving porosity change as

$$k_m = k_{m0} \frac{\phi^3}{(1-\phi)^2} \frac{(1-\phi_0)^2}{\phi_0^3},$$
(2.20)

where k_m is matrix intrinsic permeability and k_{m0} is the reference matrix intrinsic permeability. Lab measurements in tight rock have revealed that the exponent should be much larger (Kim and Makhnenko, 2020). However, once pore pressure starts to increase, the normal effective stress acting on the fracture is reduced, causing its opening. Since fracture transmissivity obeys the cubic law, fluid will preferentially flow through open fractures because of their higher transmissivity (Dippenaar and Van Rooy, 2016; Oron and Berkowitz, 1998; Witherspoon et al., 1980). Based on the parallel plate model (Huitt, 1956; Snow, 1965), the Navier-Stokes equations can be simplified to the so-called cubic law (Brush and Thomson, 2003; Zimmerman and Yeo, 2000) in which fracture transmissivity becomes

$$T_{fr} = \frac{\rho g}{\mu} k_{fr} b_{fr} = \frac{\rho g}{\mu} \frac{b_{fr}^3}{12}.$$
 (2.21)

Here, fracture permeability is assumed to be isotropic and given by $k=k_{fr}(I-M)$, where M is the tensor of the fracture plane ($M_{ij}=m_im_j$, where m is the unit vector perpendicular to the fracture), and

$$k_{fr} = \frac{b_{fr}^2}{12}.$$
 (2.22)

The dependence of transmissivity on b_{fr}^3 is the essence of the cubic law expressing that fracture transmissivity is extremely sensitive to small variations in aperture, which implies a strong coupling of fluid flow and geomechanical response of fractured rocks.

Fracture permeability can vary over several orders of magnitude as a result of fracture aperture changes. An increase in the normal loading closes fractures, reducing their permeability, while shear slip opens fractures due to dilation under low normal stresses (Rinaldi and Rutqvist, 2019; Wang, 2017), significantly increasing their permeability (Agheshlui et al., 2018; Barton et al., 1985; Min et al., 2004; Rutqvist and Stephansson, 2003; Tao et al., 2011). Notably, the permeability of sheared fractures increases more perpendicular to the direction of shear slip, thereby enhancing flow and transport connectivity in the direction orthogonal to the slip direction (Mallikamas and Rajaram, 2005; Vilarrasa et al., 2011; Yeo et al., 1998).

To account for fracture permeability enhancement as a result of changes in the effective stresses, three main approaches can be followed, where fracture permeability varies as a function of (1) strain (Lee et al., 2015; Olivella and Alonso, 2008), (2) effective stress (Min et al., 2004; Su et al., 2022; Zhou et al., 2019), or (3) pore pressure (Walsh, 1981; Zhang et al., 2017). The first approach is more physically-based because it directly relates deformation with fracture aperture changes and consequently permeability changes as (Olivella and Alonso, 2008)

$$k_{fr} = k'_{fm} + \frac{(b_0 + a\Delta\varepsilon)^3}{12a},$$
(2.23)

Where k'_{fm} is the intrinsic permeability of the matrix within the fracture zone, a is the spacing between the fractures within the fracture zone, b_0 is the initial fracture aperture, $\Delta\varepsilon$ is the volumetric strain change $\Delta\varepsilon = \varepsilon - \varepsilon_0$, and ε_0 is a threshold strain.

In the second approach, to reduce model complexity, an alternative is to use a continuum model and assume that fractures are oriented according to a certain direction. Then, the changes in the effective stress in the direction normal to the fractures are used to compute aperture changes, and from the aperture, using the cubic law, to determine fracture permeability changes (Rutqvist, 2015). It is assumed that the fracture aperture equals the residual fracture aperture for normal effective stress above a certain threshold. Below this threshold, the fracture opens up following an exponential law (Liu and Rutqvist, 2013; A. P. Rinaldi et al., 2014). Additionally, the effect of dilatancy on permeability enhancement can be included by changing the stress-dependent permeability once shear failure conditions are reached (Vilarrasa et al., 2017b).

The third category relating pore pressure with permeability is usually derived from field or laboratory measurements and thus, are case dependent and difficult to be generalized. The relationship can be made directly with pore pressure or indirectly, through another variable, like a porosity function that depends on the mean effective stress (Antonio P. Rinaldi et al., 2014; Trautwein, 2002).

2.4.6 Fracture nucleation/initiation

The phenomenon of fracture nucleation is a multifaceted process that is influenced by a variety of factors such as pore pressure, coefficient of internal friction, cohesion, elastic properties, fracture toughness, and anisotropy, among others. The nucleation of fractures can be traced to microscopic manifestations such as frictional sliding and tensile cracks along grain boundaries (Brace et al., 1966). These early indications may eventually coalesce to form a shear plane (Lockner et al., 1991). Three main modes of fracture nucleation/initiation can be differentiated: (1) Mode I, or Opening Mode; (2) Mode II, or Sliding Mode; and (3) Mode III, or Tearing Mode (Figure 2.9). The nucleation of cracks through previously intact rock can be attributed to any of these modes. In order to accurately simulate these processes through numerical methods, it is necessary to implement a constitutive model that describes the behavior of the material both before and after failure, as well as a failure criterion to determine when the material reaches its strength limit. Furthermore, a means of representing the movements associated with failure must also be incorporated, as failure results in a significant jump in the displacement field across the fracture.



Figure 2.9 Different modes of fracture initiations, (Gross and Seelig, 2017); Mode I denotes a fracture aperture symmetrically manifesting across the x, z-plane. Conversely, Mode II is distinguished by an asymmetrical disjunction of the fracture interfaces, brought about by disparate translations along the x-direction, perpendicular to the fracture forefront. Lastly, the designation of mode III encapsulates a separation due to relative displacement in z-direction, tangential to the fracture Forefront.

Tensile failure occurs in rocks when the tensile forces exceed the rock tensile strength, which is typically low (Lockner, 1995). In-situ stresses at depth are generally compressive, and therefore, tensile failure in the subsurface typically occurs when the pore pressure surpasses the least principal stress by the tensile strength. This phenomenon is the basis of hydraulic fracturing, which significantly increases the system's permeability. The occurrence of tensile failure implies a separation of the fracture edges, leading to an increase of the fracture aperture, which strongly enhances permeability. Conversely, pore pressure reduction causes the fracture to close, causing a decrease in permeability. The shear (mode II) dilation process increases the fracture aperture and, therefore, permeability due to dilation, which causes irreversible fracture opening and channeling, especially in the direction perpendicular to shear (Vilarrasa et al., 2011). All three modes should be combined to effectively stimulate reservoirs (Qin et al., 2023).

Transitional failure behavior is observable in rocks (Byerlee, 1968; Evans et al., 1990), in which a transitional failure behavior from brittle- to ductile-dominated deformation occurs with increasing effective confining stress (Walton, 2021; Wang et al., 2020; Winhausen et al., 2022; Zheng et al., 2023). This means that at low stresses, the rock breaks by forming multiple shear fractures, while at high stresses, the rock deforms by intergranular sliding and bending of grains. For a detailed review refer to (Wong and Baud, 2012).

2.4.7 Fracture propagation

Fractures, once initiated, can propagate into the surrounding rock in mode I (opening mode), mode II (sliding mode), or mixed mode (Schultz, 2000). The growth of fractures due to tensile failure is of particular importance in hydraulic fracturing operations, where the fluid pressure is deliberately increased above the least principal stress to induce fracture propagation (Bredehoeft et al., 1976). Subsequently, the fractures are filled with sand or proppant to prevent their closure and enhance the system permeability (Valkó and Economides, 1995). See a review on the initiation and propagation of fractures in intact rock in (Hoek and Martin, 2014) and a review of hydraulic fracturing simulation in (Chen et al., 2022).

Heterogeneity of the medium, like the presence of microcracks, and the local stresses affect the orientation of fracture propagation, but the key parameter that controls fracture propagation is the excess of pore pressure above the least principal stress, which strongly depends on the crack opening displacement (Yoshioka et al., 2020). The fracture toughness is only relevant in the creation of the fracture and in its initial growth (Carrier and Granet, 2012). Another important factor that controls fracture propagation is the stress interaction between fractures as they propagate (Desroches et al., 1994). Since the stress field is altered around the fractures, the propagation of adjacent hydraulic fractures may be hampered by one fast-growing fracture when multiple hydraulic fractures are formed at the same time (Lecampion et al., 2015; Lecampion and Desroches, 2015; Salimzadeh et al., 2018). Hydraulic fracture propagation has commonly been modeled considering that the fractured rock is impervious and thus, the fracturing fluid does not penetrate into the rock (Chen et al., 2022; Detournay, 2004). However, considering the actual permeability of rocks leads to a slower fracture propagation as a result of fluid leak-off (Carrier and Granet, 2012; Detournay, 2016; Salimzadeh et al., 2017).

A fracture propagation criterion is employed to determine the fracture propagation and the choice of fracture criterion largely depends on the adopted numerical scheme. In the context of discrete fracture approaches, Linear Elastic Fracture Mechanics (LEFM) and cohesive zone model are often employed. The LEFM criteria can be categorized into stress-based criteria (Irwin, 1957) or energy-based criteria (Griffith, 1921). However, for pure loading mode (e.g., mode I, or II), either stress- or energy-based criteria are identical. LEFM expresses the criteria for propagation in terms of stress intensity factors (SIF) 376. Stress-based criteria proposes that a fracture propagates when a combination of stress intensity factors at the crack tip exceeds fracture toughness. The maximum principal stress criterion (Erdogan and Sih, 1963), maximum tensile stress criterion (Rahman et al., 2000), and the maximum principal strain criterion fall under this category. Although this method is relatively easy to apply, it is highly dependent on the mesh refinement at the tips. In contrast, energy-based criteria do not require extensive refinement at the tips. In accordance with Griffith's theory (Griffith, 1921), these criteria propose that a fracture propagates when the energy release at the fracture tip exceeds a critical threshold, which is a material property (Gc, a measure of material resistance against fracturing). G-criterion (Maximum Strain Energy Release Rate Criterion) (Irwin, 1957), S-criterion (Minimum Strain Energy Density Criterion) (Sih, 1974), and F-criterion (Shen and Stephansson, 1994) are such methods. Additionally, they can be further divided according to the method utilized to numerically calculate the SIF.

The Griffith criterion (Griffith, 1921) states that a fracture line propagates when the energy release rate (J, which is the released potential energy with respect to fracture growth) reaches the critical energy release rate (Gc). The energy release rate can be calculated from the stress intensity factors in all modes of loading as

$$J = \frac{K_I^2 + K_{II}^2}{E'} + \frac{K_{III}^2}{2G},$$
(2.24)

where K_I , K_{II} , and K_{III} are stress intensity factors for opening (Mode I), shear (Mode II) and tearing (Mode III) loadings, respectively, and $E'=E/(1-\nu^2)$ for plane strain and E'=Efor plane stress.

Alternatively, cohesive zone methods, first developed by (Barenblatt, 1962; Dugdale, 1960), which are commonly used to account for non-linear mechanics effects, employ a potential to establish the relationship between cohesive tractions and the separation or slip of the fracture edges (Sarris and Papanastasiou, 2011). Therefore, fracture propagation is a gradual process that permits overcoming the stress singularities at the fracture tips calculated by LEFM (Figure 2.10). In the process zone, a traction-separation law is introduced to define the relationship between fracture width and cohesive traction. That law can take different forms, yet, in the simplest case, the fracture surfaces initiate the separation when the cohesive strength σ_c (i.e., tensile strength) is reached, and when the separation reaches a critical value δ_c (satisfying $G_c = \sigma_c \delta_c/2$), the traction decreases

linearly to zero and failure occurs (Nguyen et al., 2017; Sarris and Papanastasiou, 2011; Secchi and Schrefler, 2012). Similarly, the variational approach used in fracture propagation modifies Griffith's criterion by aiming to sequentially minimize energy (Bourdin et al., 2012; Yoshioka and Bourdin, 2016).



Figure 2.10 Schematic representation of cohesive zone model

Additionally, subcritical crack growth and the development of microcracks at the crack tip are two important phenomena, which cannot be explained by linear elastic principles of fracture mechanics (Anders et al., 2014). Subcritical crack growth manifests when fractures extend under stress intensity factors below the critical threshold (Atkinson, 1984; Ko and Kemeny, 2013, 2011; Nara et al., 2013; Orlecka-Sikora and Cielesta, 2020). As visually depicted in Figure 2.11, microcracks initially manifest in close proximity to the crack tips and progressively evolve into predominant meso- and macro-scale discrete cracks (Tejchman and Bobiński, 2012). The region immediately preceding the crack tip, denoted as the Fracture Process Zone (FPZ), represents the locus of microcrack initiation and coalescence (Vermilye and Scholz, 1998). A comprehensive investigation into the FPZ was conducted by (Brooks, 2013). This region, which plays a dual role in the fracture process, serves to ameliorate the impact of the applied load by inducing softening in the adjacent rock material and concurrently diminishes the resistance to fracture (Ortiz, 1988).



Figure 2.11 Schematic representation of fracture process zones in front of a fracture tip

2.5 Computational methods

Despite dedicated research efforts, modeling of coupled THM processes continues to present formidable challenges owing to its intricate nature. In light of the advancements in computational geomechanics, numerical techniques have emerged as robust tools, progressively employed for the investigation of fractured rock systems. However, while certain methods have been devised, not all possess the requisite capacity for effectively capturing the intricacies of the coupled processes. Simultaneously, the rapid advancements in computational capabilities have furnished a propitious environment for addressing computationally intensive challenges, thereby facilitating the development and refinement of these numerical methodologies. Consequently, the current landscape encompasses a diverse array of methods, primarily classified into two distinct categories: continuum and discontinuum-based numerical approaches. Figure 2.12 illustrates the main methods in each category. Contingent upon the continuum-based approach, the domain is discretized into constituent elements, treating the overall domain as an integrated, continuous entity. This methodological framework involves a systematic mathematical formulation incorporating a constitutive law, balance principles, as well as boundary and initial conditions. In contrast, the discontinuum-based methodologies, while relatively recent, conceptualize the domain as an assembly of discrete bodies, each capable of dynamic movement, rotation, and interactive behaviors. Consequently, their mathematical framework encompasses the interplay between individual particles and relevant balance principles. However, certain complex scenarios necessitate the amalgamation of the strengths inherent in both of these main methodologies, leading to the development of hybrid methods, coupled methods, and multi-scale coupled methods. Given the intricate and multifaceted nature of this subject, we refrain from delving into the specifics of these methodologies and instead direct the attention of interested readers to other comprehensive review articles that meticulously expound upon this particular domain (Jalali and Dusseault, 2012; Jing, 2003; Jing and Hudson, 2002; Lei et al., 2017; Mohammadnejad et al., 2021; Nikolić et al., 2016; Zhao et al., 2011).



Figure 2.12 Main numerical techniques in continuum and discontinuum-based categories to solve coupled THM problems.

2.6 Research gaps, challenges and future research directions

Since the 1960s, considerable strides have been achieved in comprehending and modeling flow and transport phenomena in deformable fractured rock. Notwithstanding these notable advancements, the endeavor to model the coupled processes of fluid flow, heat transfer, and mechanical deformation in a fractured porous medium presents a formidable conceptual and mathematical challenge. This challenge arises primarily due to three key factors:

- 1. Inherent heterogeneity and uncertainties: One of the principal impediments lies in the inherent heterogeneity and uncertainties associated with characterizing a fracture-matrix system for field-scale problems. The complex nature of these systems necessitates dealing with a wide range of variables and parameters, making accurate characterization and prediction a daunting task.
- 2. Complicated coupling processes: The complexities involved in conceptualizing, understanding, and describing flow, deformation and transport processes within intricate formation systems further contribute to the challenge.
- 3. Limitations in field fracture properties and computational intensity: Additionally, limitations stemming from measurements of field fractures (and their intersections) properties pose challenges in developing realistic three-dimensional (3D) mathematical models. The incorporation of such an intricate 3D field of fractures

demands significant computational intensity, leading to practical limitations in model development and implementation.

Addressing these challenges in modeling coupled THM processes in fractured porous media is of paramount importance to further our understanding of these systems and enhance the accuracy of predictions in real-world scenarios. The contemporary landscape of computational technologies has exerted a profound influence on the trajectory of scientific inquiry in coupled THM processes, underscoring the escalating significance of numerical modeling. However, it is vital not to solely rely on computer simulations and visualization. Attention must be paid to the fundamental theories and principles established through past experimental evidence and practical experience as well. To ensure that THM simulations are genuinely beneficial in understanding and predicting the behavior of fractured rocks within the tangible world, computational researchers should implement simulation tools realistically. This means integrating existing knowledge and empirical data from the last few decades. An additional, and often overlooked in modeling studies, imperative pertains to the setting and calibration of model parameters, which should be based on typical ranges reported in the literature. It is paramount to invoke the adage "All models are wrong, but some are useful" to highlight the value of THM models in geo-engineering and geo-resources research. However, realizing these potential calls for a methodical conceptualization, implementation, and, where feasible, calibration to foster simulation outcomes that intricately reflect the nuanced complexities of geological phenomena. Future research efforts should focus on innovative approaches to tackle these hurdles and advance the state-of-the-art in this critical field of study.

3

On the leaky nature of fractures in Low-Permeability rocks

3.1 Introduction

Fractures are ubiquitous in the subsurface, which provide permeable pathways for energy and mass transport and present both opportunities and potential issues for geoengineering applications (Adler et al., 2013). For instance, in crystalline rock, fracture permeability is sought to be increased in Enhanced Geothermal Systems (EGS) (Goto et al., 2021; McClure and Horne, 2014; Olasolo et al., 2016; Parisio and Yoshioka, 2020), but it should remain as low as possible in nuclear waste disposal (Amann et al., 2018b; Parisio et al., 2018; Xu et al., 2020) or in the caprocks for geologic carbon storage (Vilarrasa et al., 2013a) and underground hydrogen storage (Krevor et al., 2023; Xue et al., 2020). To sustainably develop and exploit geo-resources, an improved understanding of fluid flow through fractured porous media is crucial (Viswanathan et al., 2022; Zareidarmiyan et al., 2018).

Despite the small volume fraction of fractures compared to the rock volume, fluid flow and transport is controlled by fractures because they are several orders of magnitude more permeable than the surrounding rock matrix (Neuzil and Tracy, 1981). This fact commonly leads to the assumption that the rock surrounding fractures is impermeable (Koudina et al., 1998; Long et al., 1982). For instance, in most Discrete Fracture Networks (DFN) methods, the matrix is considered impervious and any flow in fractures not presented in the model is ignored (Hyman et al., 2016; Trimmer et al., 1980). Such methods are usually employed when the host rock is several orders of magnitude less permeable than fractures, such as in low-permeability limestone, shales, or granite (Fumagalli et al., 2019). However, this assumption generally leads to inaccurate predictions of the pressure changes in hydraulic tests performed in fractured media (Lin and Yeh, 2021).

In geo-resources applications, hydraulic testing is one of the few means to characterize hydrogeological properties which are essential for resource management (Illman et al., 2009; Klaas et al., 2019). In particular, hydraulic tests in fractured media are discussed in compendiums of aquifer test analysis (Beauheim et al., 2004; Cheng and Morohunfola, 1993; Kruseman and De Ridder, 1994; Nielsen, 2007; Walton, 2006). Through the interpretation of fracture hydraulic tests, accounting for the flux between fractures and rock matrix improves the predictions (Lin and Yeh, 2021). Yet, the specific contribution of leakage to pressure evolution is not fully characterized (Lee et al., 1995; Oda, 1985; Shahbazi et al., 2020; Snow, 1969; C. B. Zhou et al., 2008; Zoorabadi et al., 2022).

To interpret hydraulic tests, analytical solutions, as opposed to numerical models, are typically employed in subsurface flow and transport applications because of their practical convenience and computational efficiency (Zhou et al., 2017; Zoorabadi et al., 2022). Analytical methods are also valuable in computationally inexpensive sensitivity studies or uncertainty quantifications. They are particularly apt when dealing with a large number of injection and leaky wells, while numerical simulations would require local mesh refinement around each well to assure accurate results (Celia et al., 2011).

Even though fractures in rock masses are often interconnected, the behavior of the flow through a single fracture should be understood in detail before more complicated field-scale fracture networks can be addressed (Brown et al., 1998; Cao et al., 2019; Konzuk and Kueper, 2004; Pyrak-Nolte et al., 1988; Xiong et al., 2011; Zhang and Nemcik, 2013; Zhong et al., 2022; Zimmerman and Yeo, 2000). To tackle the challenge of representing fractures in numerical models, we propose a method to accurately simulate fluid flow in fractures represented as an equivalent continuum at a numerically tractable scale (>>10-6 m). This method differs from conventional equivalent medium models where the fracture and matrix properties are homogenized within a physically larger equivalent medium. Instead, we replace a fracture, which physically occupies a negligible space, with a physically bigger element with computationally equivalent fracture properties without homogenizing it with the surrounding rock matrix. In Appendix A, we introduce the calculation of the equivalent properties for a fracture numerically represented as a layer several orders of magnitude thicker than the real aperture. And then we verify our proposed approach against a model with the real aperture, i.e., explicit

representation of the fracture, in a case of fluid injection into a fracture surrounded by low-permeability rock matrix.

The aim of this chapter is to understand the hydraulic response of water injection into a single fracture surrounded by low-permeability rock and the implications for the interpretation of field tests. The chapter is structured as follows: first, we analyze the injection pressure evolution by comparing numerical results with analytical solutions while investigating the role of rock matrix permeability. Next, we discuss the implications of our findings for the interpretation of field-scale injection tests in fractured rock masses. Our results show that the pressure evolution in a semi-log plot corresponds to the one of a leaky fracture since early times of injection, which implies that leakage into the lowpermeability rock matrix controls pressure diffusion.

3.2 Methodology

3.2.1 Equivalent fracture layer

To model fractures, instead of explicitly representing them in a numerical model, a popular approach, namely continuum or implicit method, is to represent the fracture network as equivalent porous media. The transformation from discrete fractures to a continuum representation entails a procedure known as upscaling. Given the fracture system type, various continuum models may be employed via diverse approaches (Berkowitz, 2002; Berre et al., 2019; Flemisch et al., 2018; Wong et al., 2020). Considering a single fracture embedded in a low-permeability matrix, we use a method in which just the fracture itself is upscaled as a separate continuum than the matrix, whose properties are not modified. Upscaling follows analytical-based methods to calculate the equivalent properties related to the equivalent fracture layer (Figure 3.1).

Consider fluid injection into a saturated fracture surrounded by low-permeability rock matrix: transient flow through a confined layer is governed by the flow equation (Bear, 1972)

$$\nabla \cdot (T\nabla s) = S \frac{\partial s}{\partial t} + f_w, \qquad (3.1)$$

where S is the storage coefficient, $s = p/\gamma_w + z$ is the hydraulic head, t is time, and f_w is a sink/source term. The left-hand side of Eq. (3.1) corresponds to flux, which is controlled by the transmissivity, and the first term in the right-hand side to storage, which depends on the storage coefficient. To obtain identical solutions of Eq. (3.1) between a fracture with its actual aperture and an equivalent fracture layer with upscaled thickness (Figure 3.1), the same transmissivity and storage coefficient have to be applied in the two problems.



Figure 3.1 Conceptualization of the equivalent fracture layer with upscaled thickness and how to obtain its equivalent properties from the actual fracture ones

The transmissivity of a layer is calculated as

$$T = Kh = \frac{\rho g}{\mu} kh, \qquad (3.2)$$

where K is the hydraulic conductivity, h is the thickness of the layer, ρ is the fluid density, g is gravity, μ is the fluid viscosity and k is the intrinsic permeability. If flow through a fracture is regarded as the parallel plate model (Huitt, 1956; Snow, 1965), we can simplify the flow rate from the Navier-Stokes equations to the so-called cubic law (Brush and Thomson, 2003; Witherspoon et al., 1980; Zimmerman and Yeo, 2000; Zou et al., 2015), in which fracture transmissivity, T_f , becomes

$$T_f = \frac{\rho g}{\mu} k_f b_f = \frac{\rho g}{\mu} \frac{b_f^3}{12} , \qquad (3.3)$$

where b_f is fracture aperture and the fracture permeability, k_f , equals

$$k_f = \frac{b_f^2}{12}.$$
 (3.4)

The storage coefficient of a fracture, S_f , is defined as

$$S_f = S_S b_f = \gamma_w (\varphi_f \beta_w + \beta_r) b_f \tag{3.5}$$

where S_S is the specific storage coefficient, φ_f is the fracture porosity, β_w is the water compressibility and β_r is the bulk compressibility of the fracture. Fracture porosity equals 1 for open clean fractures, but can take lower values if the fracture has gouge or asperities.

The equivalent permeability, k_{eq} , of the equivalent fracture layer can be calculated by equating Eqs. (3.2) and (3.3), resulting in

$$k_{eq} = \xi k_f, \tag{3.6}$$

where

$$\xi = \frac{b_f}{b_{eq}},\tag{3.7}$$

and b_{eq} represents the thickness of the equivalent continuum fracture layer (Figure 3.1).

Similarly, the equivalent porosity can be derived from Eq. (3.5) as

$$\varphi_{eq} = \xi \varphi_f, \tag{3.8}$$

where the equivalent parameter ξ is the same as for permeability (Eq. (3.7)).

For fluid injection into a fracture, the injected volumetric flow rate, Q, must be maintained in order to obtain the same solution when upscaling fracture thickness with the equivalent fracture layer approach. Given that the flux injected into a layer through a fully penetrating well equals Q/A, where A is the area where fluid is injected, i.e., $2\pi r_w h$, r_w being the radius of the well, the equivalent injection flux into the equivalent fracture layer, q_{eq} , should be

$$q_{eq} = \xi q_f, \tag{3.9}$$

where $q_f = Q/(2\pi r_w b)$ is the injection flux for the actual fracture.

3.2.2 Analytical solutions of pressure evolution

Since 1930s, many works have been carried out to characterize the transient flow of pumping/injection tests performed in naturally or artificially fractured aquifers (Barker, 1988; De Smedt et al., 2018; Delay et al., 2007; Dewandel et al., 2014; Hamm and Bidaux,

1996; Jourde et al., 2002; Moench, 1984; Muskat, 1938; Russell and Truitt, 1964; Tiab, 2005; Warren and Root, 1963). As a result, several analytical solutions have been developed to reproduce the flow behavior induced by a well intersecting and pumping/injecting a vertical, horizontal or inclined permeable layer (Cheng and Morohunfola, 1993; Cinco Ley et al., 1978; Gringarten et al., 1974; Hantush, 1960; Hantush and Jacob, 1955; Moench, 1985; Neuman and Witherspoon, 1969; Ramakrishnan and Kuchuk, 1993; Theis, 1935). More recent solutions improve earlier works considering less restrictive assumptions on flow conditions in the aquitard, representing more realistic aquitards, and obtaining more accurate model prediction (Cihan et al., 2011; De Smedt, 2022, 2011; Dewandel et al., 2018; Zhou et al., 2009).

The problem of fluid injection into a planar fracture surrounded by low-permeability rock matrix is analogous to problems of hydrogeology of fluid flow into thick aquifers which have analytical solutions. If the confining layers can be considered impermeable, the Theis solution (Theis, 1935) applies; but if leakage into the surrounding lowpermeability rock matrix is non-negligible, then the solution of Hantush for leaky aquifers should be used (Hantush, 1960). Given the low-permeability of the rock matrix (particularly in crystalline and shaly rocks), it is commonly assumed that the rock matrix is impermeable, as in DFN approaches.

For the former situation, i.e., impermeable confining layers, considering injection at a constant flow rate through a fully penetrating well into a confined saturated aquifer and assuming homogeneity and infinite lateral extent, the hydraulic response to water injection can be computed analytically as (Theis, 1935):

$$s = \frac{Q}{4\pi T} \int_{u}^{\infty} \frac{e^{-y}}{y} dy = \frac{Q}{4\pi T} W(u), \qquad u = \frac{Sr^{2}}{4Tt}$$
(3.10)

where Q is the injected volumetric flow rate, T is the transmissivity, p is the fluid pressure, γ_w is the specific weight of the fluid, z is the elevation from an arbitrary plane, r is the radial distance from the well, and W(u) is the so-called well function.

Based on the Theis solution, several methods have been developed to estimate transmissivity and the storage coefficient from the pressure evolution (Chow, 1952; De Smedt, 2022, 2011; Jacob, 1947, 1940; Jacob and Lohman, 1952). The most used approximation is the one proposed by (Cooper Jr and Jacob, 1946):

$$s = \frac{2.3Q}{4\pi T} \log\left(\frac{2.25Tt}{Sr^2}\right).$$
 (3.11)

If we plot drawdown against radial distance (r) and time (t), the curves cross distance/time axes in certain points (at s=0). Defining those points as the radius of influence, R, and the response time, t_0

$$R = \sqrt{\frac{2.25Tt}{S}}, \qquad t_0 = \frac{Sr^2}{2.25T}, \qquad (3.12)$$

the solution becomes

$$s = \frac{2.3Q}{2\pi T} \log\left(\frac{R}{r}\right) = \frac{2.3Q}{4\pi T} \log\left(\frac{t}{t_0}\right),\tag{3.13}$$

where R represents the pressurization front when no leakage occurs to the confining layers and scales with the square root of time.

Eq. (3.13) shows two important properties of the aquifer response to injection. The first one is that pressure buildup follows a linear log distribution of distance from the well: injection causes a cone-shaped pressure profile along the radial direction. The size of the cone grows in a self-similar manner with time. The cone is centered at the well and its external radius evolves with the radius of influence R (Eq. (3.12)). The second one is that when pressure changes are plotted against log t, they follow a straight line whose slope (m) is inversely proportional to the transmissivity and intercepts the time axis at t_0 . Consequently, the transmissivity and the storage coefficient can be estimated as

$$T = \frac{2.3Q}{4\pi m} = 0.183 \frac{Q}{m}, \qquad S = \frac{2.25Tt_0}{r^2}.$$
 (3.14)

The linear relationship of pressure changes against $\log(t)$ under radial flow conditions prompted researchers to use the derivative of pressure changes with respect to log time as an interpretation method (Bourdet et al., 1989, 1983). The joint representation of the pressure changes and its log-derivative, known as diagnostic plots (Renard et al., 2009), can be highly informative. The flow dimension, d, can be calculated from the slope n of the log-derivative as a function of time in a log-log plot as (Niemi et al., 2017):

$$d = 2(1 - n). \tag{3.15}$$

Considering the leaky nature of the system, the drawdown in the fracture shows typical characteristics inherent in double-porosity behavior in which the matrix is considered as a primary porous system with low hydraulic conductivity and high storage capacity and the fractures as a secondary porous system with high hydraulic conductivity and low storage capacity (Hamm and Bidaux, 1996). In the double-porosity concept, the initial drawdown is due to the fracture storage as if the rock matrix were non-existing (first stage); leakage gradually gains weight and the matrix storage becomes dominant (second stage); and eventually the whole medium acts as a homogeneous system with the storage capacity of the fractures and matrix combined (third stage) (De Smedt, 2022). For situations in which fracture spacing is large, in the dm scale, and the permeability of the rock matrix is several orders of magnitude lower than that of fractures, the first stage disappears immediately and it requires a long time to reach the third stage (homogeneous system). As a result, only the first and second stages and the transition between them are relevant. Such situations are our focus in this chapter.

Early analytical solutions to the leaky aquifer problem neglected the storage of the confining layers (Hantush, 1956; Hantush and Jacob, 1955), while a generalized expression that accounts for storage of the confining layers was later proposed by (Hantush, 1960), which reads

$$s = \frac{Q}{4\pi T} \int_{u}^{\infty} \frac{e^{-y}}{y} \operatorname{erfc}\left(\beta \sqrt{u} / \sqrt{y(y-u)}\right) dy = \frac{Q}{4\pi T} H(u,\beta), \qquad (3.16)$$

where

$$\beta = \frac{r\lambda}{4}, \qquad \lambda = \sqrt{\frac{K'/b'}{T}\frac{S'}{S}} + \sqrt{\frac{K''/b''}{T}\frac{S''}{S}}, \qquad (3.17)$$

and K is the hydraulic conductivity, b is the thickness of the layer, H is the Hantush well function, and superscripts ' and " denote the properties associated to the upper and lower confining layers, respectively. We compute the Hantush well function by numerical integration. The solution is valid for time lower than both b'S'/10K' and b''S''/10K'': at these times, the pressure perturbation reaches the upper and lower boundaries. (Veling and Maas, 2010) reviewed several representations of the Hantush well function and introduced a practical and fast approximation. The Hantush well function can be approximated by (Hantush, 1960)

$$H(u,\beta) \approx W(u) - \frac{4\beta}{\sqrt{\pi u}} (0.2577 + 0.6931e^{-u/2})$$
 (3.18)

for early time or $u\geq 10^4\beta^2,$ and by

$$H(u,\beta) \approx \frac{1}{2} \ln\left(\frac{0.044}{\beta^2 u}\right) \tag{3.19}$$

for $u \leq 10^5/\beta^2$ and $u \leq 10^{-4}\beta^2$. The transition between these approximations happens in $u = \beta^2$ and based on that, we can define the transition time as

$$t_t = \frac{S_s b^2}{K'},$$
 (3.20)

where S_s is the specific storage coefficient. The radius of influence for leaky aquifers can be obtained by numerical integration of the Hantush solution or more simply using the approximation in Eq. (3.19). The radius in which the approximation for the Hantush well function reaches zero is

$$R = \sqrt[4]{\frac{0.704T^2b't}{K'S'}}.$$
(3.21)

I generalize the problem using the following dimensionless variables

$$t_D = \frac{t}{t_c}; \ s_D = \frac{s}{s_c}; r_D = \frac{r}{L_c}; \phi_D = \frac{\phi}{\phi_c} \text{ and } k_D = \frac{k}{k_c},$$
 (3.22)

where ϕ is the porosity, k is the intrinsic permeability, L is length, and the subscripts D and c denote dimensionless and characteristic variables, respectively. Based on the hydraulic boundary condition, i.e., a constant flow rate, the characteristic hydraulic head can be defined as

$$s_c = \frac{Q\mu}{2\pi b\rho gk_c},\tag{3.23}$$

where ρ is the fluid density, g is gravity, and μ is the fluid viscosity. The characteristic length, porosity, and permeability are chosen as the well radius and porosity and permeability of the fracture, respectively (i.e., $L_c = r_w$, $\phi_c = \phi_f$, and $k_c = k_f$). The characteristic time can be defined from the flow equation, yielding the characteristic time of diffusion

$$t_c = \frac{L_c^2 S_s \mu}{\rho g k_c}.$$
(3.24)

3.2.3 Numerical modeling

We numerically model a fracture both explicitly and implicitly using an equivalent fracture layer. We use an axisymmetric model to represent a single circular fracture in which water is injected in the center through a well with a radius of 0.1 m, i.e., $L_c=0.1$ m (Figure 3.2). The fracture is horizontal, confined, and with uniform thickness. The model represents a fracture with a radius of $L_D=10^4$ embedded between two thick layers of low-permeability rock ($b_{mD}=100$) at a depth of $z_D=10^4$. Each continuum, i.e., the fracture continuum and the matrix continuum, is assumed to have homogeneous and isotropic hydraulic properties. The radial extent of the fracture is such that the nature of the outer boundary, i.e., constant pressure or no flow, does not affect results during the duration of injection, i.e., the radius of influence (Eq. (3.21)) is smaller than the radial extent of the model. A linear hydrostatic pressure gradient is applied to the model as the initial condition. The injection is at a constant rate ($q = 50 \text{ kg/s/m}^2$) and the flow in the fracture is described by the classical groundwater flow equation (Barenblatt et al., 1960; Bear, 1972; Moench, 1984; Warren and Root, 1963).



Figure 3.2 Schematic representation of the axisymmetric model geometry and initial conditions; a flux q_D is injected in the center of a $L_D=10,000$ radius fracture with aperture b_{eqD} . The properties of the confining rock matrix are denoted by subscript 'm'.

The reference model explicitly represents the fracture by discretizing the actual fracture aperture of 10^{-5} m. The fracture permeability is calculated using the cubic law (Eq. (3.4)), resulting in $8.33 \cdot 10^{-12}$ m². The fracture porosity is set to 0.1. The permeability and porosity of the confining layers are 10^{-19} m² and 0.1, respectively. The reference solution is the one given by a model that represents the actual aperture, i.e., explicit
representation of the fracture. We build several additional models with increasing thickness of the equivalent fracture layer and apply the equivalent properties, i.e., permeability, porosity, and injection flux rate, to each model using the relationships given in Equations (3.6)-(3.9) (Table 3.1). Equivalent properties are set to impose a constant fracture transmissivity ($8.33 \cdot 10^{-10} \text{ m}^2/\text{s}$), storage coefficient ($4.41 \cdot 10^{-12}$), and flow rate ($3.14 \cdot 10^{-4} \text{ kg/s}$).

Neglecting the solid phase compressibility, the same storage coefficient is assumed for the matrix. The model simulates water injection at a constant rate for 300 hours and we analyze the pressure evolution at the injection well and the pressure profile along the fracture at the end of injection. (Birkholzer et al., 2009) demonstrated the influence of leakage on lowering pressure buildup (pressure bleed-off) in the aquifer for aquitard permeability as low as 10^{-18} m². To investigate lower permeability, we carry out a sensitivity analysis to assess the effect of the rock matrix permeability on pressure evolution by taking values in the range from 10^{-18} to 10^{-24} m² for 100 hours of injection using an equivalent fracture layer with an upscaled thickness of 1 cm.

Ratio of the equivalent fracture layer b_{eq} to the fracture aperture b (1/ ξ)	Permeability k _{eqD}	Porosity φ_{eqD}	Injection flux <i>q_{eqD}</i>
1	1	1	1
10 ³	10-3	10-3	10-3
10 ⁴	10-4	10-4	10-4
2.5.104	$4 \cdot 10^{-5}$	$4 \cdot 10^{-5}$	4·10 ⁻⁵
5.104	2·10 ⁻⁵	2.10-5	2.10-5
10 ⁵	10-5	10-5	10-5

Table 3.1 Input parameters for the fracture and equivalent fracture layer models

We employ the Finite Element Method (FEM) numerical program CODE_BRIGHT (Olivella et al., 1996). We use structured mesh including 12,322 quadrilateral elements. The mesh configuration is the same for all models in which the fracture has 10 vertical elements and the matrix slabs have 30 elements in the vertical direction. The elements in the matrix are concentrated toward the fracture-matrix interfaces to accurately capture leakage effects. The horizontal distribution of the elements has refinement toward the

well. We have performed a mesh sensitivity analysis to ensure that further refinement does not affect the results.

3.3 Results

Equivalent fracture layer models can simulate pressure evolution accurately (figure 3.3). Even the models with large upscaled thicknesses reproduce the results of the actual aperture model after a short time. At early time (dimensionless time lower than 1), simulation results from large upscaled thickness deviate from the benchmark solution (real fracture) because the flow within the equivalent fracture layer is not 1D radial and the pressure diffusion normal to the layer plays a role in the pressure evolution. The equivalent approach to model a fracture will work if the porous layer can be considered thin enough to assume 1D flow within the element. The equivalent fracture layer reproduces the pressure evolution well after

$$t_D > C \frac{b_{eqD}^2}{D_{vD}} \tag{3.25}$$

where D_{v} is the vertical pressure diffusivity and C is a coefficient that depends on the equivalent fracture thickness. For $b_{eqD} > 10^{-2}$, $C = 13.2 \cdot b_{eqD}^{2} + 191.5 \cdot b_{eqD} - 130.4$, while for values of $b_{eqD} < 10^{-2}$, the equivalent fracture layer yields the same results as the actual fracture in less than milliseconds.



Figure 3.3. Dimensionless pressure evolution at the injection well for equivalent fracture layer models with increasing ratio of the equivalent fracture layer thickness to the fracture aperture $(1/\xi = b_{eq}/b_f)$ during

constant flow rate injection. The solid black line is the response of the real fracture aperture and other colors are associated to models with upscaled thickness using equivalent parameters

Equivalent fracture models are accurate during the whole injection time when the ratio of the equivalent fracture layer to the actual fracture aperture, i.e., $1/\xi$, is lower than or equal to 10^3 . The pressure evolutions shown in Figure 3.3 include solo-fracture stage as well as fracture-matrix stage with leakage, but not the final stage in which the fracture and matrix act as a single medium. These curves display the typical pressure evolution with constant slope in a semi-log plot, from which the transmissivity and storage coefficient can be derived. Also, all models yield an identical pressure distribution along the middle of the fracture aperture or the upscaled thickness at the end of the injection phase (Figure 3.4). The pressure perturbation extends up to $r_D=1000$, which is much smaller than the radius of influence in a confined fracture within impervious layers (Eq. (3.12)), and corresponds to the radius of influence when leakage dominates (Eq. (3.21)).



Figure 3.4 Dimensionless pressure profile along the dimensionless radial coordinate measured at the middle of the fracture aperture or the equivalent fracture layer at the end of the injection for the reference model with the actual fracture aperture and equivalent fracture layer models with different thickness. All models give identical results

Simulation results show that the thickest equivalent fracture layers yield identical results to the actual aperture model after a short period, which defines the limit of applicability of the method. For different equivalent apertures, the results are eligible after a certain time, given by Eq. (3.25). On the one hand, one can use thick equivalent fracture layers for applications in which the pressure evolution and distribution in early times are

not relevant, like for long-term geothermal energy production. On the other hand, thinner equivalent fracture layers should be used when early times are of importance, like in interpretation of injection tests. To achieve accurate results during the whole injection time, it is sufficient to represent fractures with a thickness of 10 cm $(1/\xi=b_{eq}/b=10^4)$. Such thickness permits multiple fractures in models, although the treatment of fractures intersection may pose additional challenges, which will be a topic of future research

Fracture transmissivity and storage coefficient can be obtained based on the pressure evolution measurements from the slope and intercept of the curve (Renard et al., 2009). A simulation result with $k_{mD} = 1.2 \times 10^{-8}$ shows an initial transition phase dominated by the storage effect, which is followed by a straight line in a semi-log plot (Figure 3.5). The Theis solution can be fitted with a transmissivity that is twice the actual fracture transmissivity, and 5 times the real storage coefficient. This storage coefficient would correspond to a fracture with an aperture of $b'_{eqD} = 5 \times 10^{-4}$. The Theis solution can be reproduced if we neglect the matrix permeability and porosity in the numerical model (see the solid and dashed blue lines in Figure 3.5). This demonstrates that the neglecting the rock permeability can lead to huge errors in curve-fitting interpretation with the Theis solution.



Figure 3.5 Dimensionless pressure evolution response to injection into a fracture surrounded by lowpermeability rock resulting from numerical and Theis solutions. The solid black line is the pressure produced by the numerical model, the dashed black line is the Theis solution considering the real fracture properties and the dashed red line is the fitted straight line to estimate transmissivity and the storage

coefficient, resulting in a transmissivity that is twice that of the fracture and a storage coefficient five times larger, which would imply a fracture aperture b'_{eqD} of 5.10⁻⁴, 5 times larger than the actual one

Next, we perform a sensitivity analysis to dimensionless rock matrix permeability ranging from 1.2×10^{-7} to 1.2×10^{-13} (Figure 3.6). The slope that would correspond to twice the actual fracture transmissivity appears immediately after injection in the cases with the rock matrix permeability up to 1.2×10^{-9} . For the cases with a lower permeability, the enhanced transmissivity slope does not immediately appear. Instead, the pressures first follow a steeper slope that corresponds to the slope of the actual fracture transmissivity, and then the slope that corresponds to a hither transmissivity. The lower the rock matrix permeability is, the longer the transition time between the two slopes becomes. The transition time (shorter than a few seconds in all cases) is proportional to the rock matrix permeability, i.e., one order of magnitude smaller rock matrix permeability implies a one order of magnitude longer transition time.



Figure 3.6 Dimensionless pressure evolution response to a wide range of dimensionless rock matrix permeability and the corresponding dimensionless transition time, t_{tD} , for each case. The solid black line indicates the fitted Theis solution (same transmissivity as the real fracture transmissivity, but modified storage)

We analyze the slopes and transition time for the case of rock matrix permeability of $k_{mD} = 1.2 \times 10^{-12}$ (Figure 3.7). The first slope that arises only for the lowest matrix permeabilities corresponds to that of the real fracture transmissivity (indicated by the

solid black line in Figure 3.6 as well as phase I in Figure 3.7). Nonetheless, the interpreted storage coefficient (from the Theis solution) is 2.5 times the actual fracture one, which would be equivalent to a fracture aperture of $b'_{eqD} = 2.5 \times 10^{-4}$. After a transition, the slope turns into twice the actual fracture transmissivity and a storage coefficient that is $4 \cdot 10^{-4}$ times that of the actual fracture (phase II in Figure 3.7). The transition time between these two phases can be estimated from the intersection of the fitted straight lines of each phase, giving a value of $t_{tD} = 10^4$.



Figure 3.7 Phases of the pressure evolution and fitting of transmissivity and storage coefficient for each phase (using Theis solution) for a dimensionless rock matrix permeability of 1.2×10^{-12} . The solid orange line is the pressure from the numerical simulation with leakage, the solid dark blue line is from numerical simulation neglecting any transfer between the fracture and the matrix, the dashed cyan and red lines are the fittings for each phase, and the dashed blue line is the expected pressure evolution when applying the analytical solution of Theis for this problem.

To explore the contribution of leakage on the pressure evolution, we compare simulation results with the Hantush (1960) solution (Eq. (3.8)) (Figure 3.8). At early times, i.e., during phase I in Figure 3.7, which lasts for a short period (in the order of milliseconds to seconds), numerical results deviate from the Hantush solution. In phase I, the slope of the pressure evolution in a semilog plot presents the actual fracture transmissivity (the same as in the Theis solution), but with more storage, provided by the matrix. In other words, the extra storage provided by the matrix becomes effective sooner in the numerical model compared to the Hantush solution. In fact, both storage and transmissivity of the matrix activate together in Hantush's solution (based on the assumptions of a thick aquifer), but storage of the matrix starts to play a role sooner than the transmissivity of the matrix in the numerical solutions (Figure 3.8) (See Figure 3.9 for more details). In addition, the analytical solution may also introduce some errors at early times because it relies on the quasi-steady-state assumption for continuum flow, which is not satisfied during the early rapid transient flow. Therefore, the numerical solution is more accurate for early time behavior. After the transition time, simulation results fit the Hantush solution for the double-transmissivity slope, i.e., when there is leakage into the low-permeability matrix (phase II in Figure 3.7). This fitting confirms that fractures surrounded by low-permeability rocks have a leaky nature.



Figure 3.8 Dimensionless pressure evolution as a result of injection into a fracture calculated with numerical and the Hantush (1960) solutions for two different permeability of the confining rock matrix. The Theis (1935) solution is also included for comparison purposes. Deviation from the Theis solution, which assumes impermeable rock matrix, occurs in less than a second when the rock matrix permeability is 12 orders of magnitude smaller than the fracture permeability

In our analysis, the porosity of the matrix is $\phi_{mD}=1$, causing a difference in the earlytime response between numerical and Hantush's solution (Figures 3.8 & 3.12). A detailed look at the pressure evolutions during Phase I (defined in Figure 3.7) in Figure 3.9 reveals that in the numerical model, the storage of the matrix starts to play a role sooner than the transmissivity of the matrix compared to the analytical solution in which both transmissivity and storativity act simultaneously. However, in the case of the lower matrix porosity ($\phi_{mD}=0.1$), i.e., negligible matrix storage, there is no difference between numerical result and both analytical solutions during phase I, showing that the rock matrix behaves as completely impermeable. Thus, the difference between the numerical and Theis solution in our base case (red line in Figure 3.9) is due to storage of the matrix. Matrix storage has also an effect on the long-term pressure evolution: the larger the storage, the lower the pressure build-up at a given time (compare the colored continuous (high matrix storage) and colored dashed lines (low matrix storage) in Figure 3.9). Despite the vertical shift in the pressure evolution curves by decreasing the matrix porosity, transition time to Phase II remains the same.





Hantush (1960) solutions for two different porosities of the confining rock matrix (i.e., 0.1 and 0.01; dimensionless matrix permeability of 1 and 0.1, respectively) (dimensionless permeability of the matrix is 1.2×10-12). The Theis (1935) solution is also included for comparison purposes (it is independent from the matrix porosity).

As the leaky nature of fractures depicts the twice higher fracture transmissivity on the semi-log plot, one may try to double the fracture transmissivity in numerical models with impermeable rock matrix to obtain accurate results. Such a manipulation would result in a reasonable pressure evolution at the well (Figure 3.10). However, the pressure distribution along the fracture would be significantly different from what it should be because of the pressure front propagation speed (compare the radius of influence when neglecting and considering leakage (Eqs. (3.12) and (3.21), respectively)). While the simulated pressure distribution with leakage agrees well with that of Hantush (Figure 3.10), the distribution differs by more than two orders of magnitude from Hantush's solution if the rock matrix permeability is neglected (Figure 3.10).



Figure 3.10 Dimensionless pressure profiles along the fracture at the end of the injection, predicted by the numerical (red line) and the Hantush (1960) solutions for a dimensionless permeability of the rock matrix of 1.2×10⁻⁸. Two blue lines are the results of numerical simulations where fracture-matrix transfer is neglected (Note that the dashed line model employs double permeability for the fracture)

We investigate what causes different pressure evolutions between numerical and analytical (Hantush, 1960) solutions using diagnostic plots for the case of dimensionless rock matrix permeability equal to $k_{mD} = 1.2 \times 10^{-12}$ (Figures 3.11 and 3.12). Diagnostic plots help identifying the flow regime during fluid injection by simultaneously plotting the pressure and the logarithmic derivative of the pressure in semi-log and log-log plots. The logarithmic derivative magnifies subtle variations in the pressure evolution and allows us to detect behaviors often overlooked on the pressure evolution curve alone. The straight black lines in Figure 3.11 unveil the flow regimes from their slopes (Renard et al., 2009). At the beginning of injection, the log-derivative of pressure in a log-log plot presents a slope of 1/4, which corresponds to a flow dimension of 1.5 (Eq. (3.15)), i.e., between linear and radial. The Hantush (1960) solution has an initial slope of 1, which corresponds to a flow dimension equal to 0 (Eq. (3.15)). This discrepancy brings the numerically simulated curve downward during phase I (Figures 3.8 & 3.9). In phase I, the flow regime turns into radial, as shown by the constant pressure derivative. In this initial phase, flow is confined within the fracture and the surrounding rock matrix acts as an impermeable boundary, as shown by the slope of the pressure evolution corresponding to that of the actual fracture transmissivity (Figure 3.7). This radial flow regime lasts for a limited time and turns into a slope of -1/4 in the log-log derivative plot, i.e., a flow dimension of 2.5 (Eq. (3.15)), which is between radial and spherical (Figure 3.11). This flow regime indicates the onset of leakage from the fracture into the rock matrix. When compared with the diagnostic plots of the Hantush (1960) solution, the flow dimension of this transient stage is 2.15, which is closer to radial (Figure 3.12). The lower flow dimension in the second transient stage in Hantush (1960) leads to slight differences in the pressure evolution with respect to the numerical solution. Finally, the flow becomes radial again, but with a value of the pressure derivative that is half of the first radial flow, i.e., the effective transmissivity of the system becomes twice higher than the fracture transmissivity (phase II in Figure 3.7). The latter radial flow implies not only flow along the fracture, but also into the low-permeability rock matrix.



Figure 3.11 Diagnostic plot for the case with dimensionless rock matrix permeability of 1.2×10^{-12} . The blue dots are the pressure derivative, the red dashed line is pressure evolution, and the solid black line is the flow regime trend based on the pressure derivative.



Figure 3.12 Diagnostic plots of the numerical and the Hantush (1960) solutions for the case with dimensionless rock matrix permeability of 1.2×10⁻¹² in (a) log-log and (b) semi-log diagrams. Derivative of dimensionless pressure evolutions (scatter curves) correspond to the first y-axis (on the left) and dimensionless pressure evolutions (dashed lines) to the second y-axis (on the right).

3.4 Discussions

3.4.1 Implications of the leaky nature of fractures in hydraulic-test interpretation

We have analyzed the pressure evolution during fluid injection into a single fracture surrounded by low-permeability rock matrix and found that leakage into the matrix occurs from early times (milliseconds to seconds), reducing the slope of the pressure evolution in a semilog plot by a factor of two, which corresponds to a twice higher fracture permeability in the Theis solution. For interpretation of hydraulic tests in fractures, it is important not to neglect leakage even in low-permeability rock matrix (Figure 3.6). In practice, it is challenging to record pressures with higher frequencies than every few second and pressure measurements during the first few seconds of injection may be noisy or masked by wellbore effects. If measurements at early times are missed, the pressure evolution would depict a straight line with log t, which could be misinterpreted as the pressure evolution with no leakage into the low-permeability matrix (e.g., Figure 3.5). Thus, using conventional methods for interpreting field tests (e.g., Cooper & Jacob, 1946), one may erroneously interpret the fracture permeability twice higher than the actual permeability. If this double permeability were used in analytical or numerical models to estimate the pore pressure propagation into the fractured rock, the pressure at the injection well would be accurately estimated, but the pressure propagation into the fracture would be overestimated by a few orders of magnitude (Figure 3.10).

This factor of 2 arises from the difference in the slopes of the pressure change as a function of log t given by the solutions of Theis (1935) (for a layer confined by impermeable boundaries) and Hantush (1960) (for a leaky layer). Their slopes are given by the time derivative of Eqs. (3.10) and (3.16), respectively. The functions W(u) and $H(u,\beta)$ do not have an analytical expression of their time derivative, but we can use their approximations. The slope becomes $Q/(4\pi T)$ for the case of impermeable confining layers and $Q/(8\pi T)$ for the case of leaky confining layers. Leakage actually occurs when injecting into fractures surrounded by very low-permeability rock, giving rise to a slope that is half of the one of Theis (1935). Thus, neglecting leak-off in the interpretation of field tests overestimates fracture transmissivity, which may give rise to erroneous predictions in numerical models.

The typical pressure response to fluid injection into a fractured aquifer is as follows (Cinco-Ley and Meng, 1988; De Smedt, 2011). In a semi-log graph (Figure 3.13), the

pressure curve shows two parallel straight lines representing the fracture dominated flow (Phase I) and the total system (fracture-matrix) dominated flow (Phase III). There is a transition period between these parallel lines (Phase II) called stabilization period in which the pressure curve, for the transient matrix flow, is represented by a straight line whose slope is half the slope of the parallel lines. The pressure evolution initially follows the Theis solution as storage and leakage into the matrix are negligible (dark blue line in Figure 3.13). Subsequently, the injected fluid starts to leak into the rock matrix, reducing the slope of the pressure as a function of the logarithm of time by a factor of two, as reproduced by the Hantush solution (red line in Figure 3.13). Pressure diffusion into the rock matrix eventually leads to pressure equilibration between the pressure in the fracture and the pressure within the rock matrix blocks (Zareidarmiyan et al., 2021). After equilibration, the pressure gradient between the fracture and the rock matrix becomes negligible, hindering fluid flow from the fracture to the matrix, and the whole system is controlled again by the fracture permeability, recovering the initial slope (light blue line in Figure 3.13). In a fractured aquifer, the rock matrix permeability is orders of magnitude higher than in tight rocks (such as in low-permeability shales or granite) as assumed in this study. As a result, we do not observe phase III because, for the time scale of our analysis, i.e., a few hundreds of hours, pressure diffusion does not propagate into the rock matrix. Additionally, Phase I only lasts for less than a few seconds, depending on the rock matrix permeability (Figure 3.6). Hence, in a field test, which typically lasts for a few hours, one may miss the first few seconds of pressure measurements and only observe the second phase. For this reason, bearing in mind the leaky nature of fractures is essential to interpret tests and derive the proper fracture properties.



Figure 3.13 Typical drawdown versus log-time curves for a pumping/injection test in a fractured aquifer, the dark blue line is the fracture Theis solution (upper bound). The light blue line is the fracture-matrix Theis solution (when both fracture and matrix act as a single system).

3.4.2 Implications of the leaky nature of fractures in modeling subsurface applications

The transition time at which leakage becomes non-negligible depends on the subsurface application. This transition time affects the ability to characterize and model these systems. To assess the role of leakage into the surrounding low-permeable rock, we estimate the transition time at which the slope of the pressure evolution curve is reduced by a factor of 2 for several geo-energy, geo-engineering, and water resources applications (Table 3.2). Isolines of the transition time are parallel straight lines when plotted as a function of the thickness of the injection layer and the permeability ratio between the lowpermeable rock and the injection layer (Figure 3.14). Two groups of applications can be distinguished. On the one hand, transition times are short for the applications in which fluids are injected into or produced from fractured tight rock, like Enhanced Geothermal Systems (EGS), hydraulic fracturing (HF) and groundwater pumping from fractured aquifers (GWFM), indicating that leakage dominates almost from the beginning of injection. On the other hand, longer transition times are expected for the applications in which fluids are injected in or produced from thick permeable layers, like waste water disposal (WWD), Carbon Capture and Storage (CCS), compressed air energy storage (CAES), hydrogen storage, and groundwater production from aquifers (GWA). In some occasions transition times may be longer than the duration of the operation and, hence, the effect of leakage may be ignored. However, to obtain reliable long-term estimates, leakage must be considered from the beginning, both in well-test interpretation and in numerical simulations, in applications in which fluids are injected into or produced from fractures surrounded by low-permeability rock (applications placed in the left-hand side of Figure 3.14), regardless of how low is the permeability of the rock matrix

geo-engineering, and water resources applications							
Application	nanced thermal ns (EGS)	traunc turing HF) arbon	ge (CCS) te water sposal VVD)	pressed Energy orage AES)	drogen orage	ndwater aquifers ;WA)	ndwater fractured nedia WFM)

Table 3.2 Dimensionless transition time at which leakage becomes non-negligible for several geo-energy, geo-engineering, and water resources applications

	Applicatio	on	Enhance Geothern Systems (E	Hydraul fracturir (HF)	Carbon Capture a Storage (C	Waste wa disposa (WWD)	Compress Air Ener Storage (CAES)	Hydroge storage	Groundwa from aquil (GWA)	Groundwa from fractu media (GWFM
]	Dimensionless	Max	107	108	9×10 ¹⁴	6×10 ¹⁴	3×10 ¹³	1014	1014	10 ²¹
tra	ransition time	Min	10-7	10-8	107	2×10 ⁹	10 ⁵	107	107	10 ¹⁵



Figure 3.14 Dimensionless transition time at which leakage becomes non-negligible as a function of the ratio between matrix and injection layer permeability, and the ratio of the injection layer thickness and the well radius (characteristic time is the same as Eq. (9)). The range of transition time is indicated for several geo-energy and geo-engineering applications (EGS: Enhanced Geothermal Systems; HF: Hydraulic fracturing; CCS: Carbon capture and storage; WWD: Waste water disposal; CAES: Compressed air energy storage; H2 storage: Hydrogen storage; GWA: Groundwater from aquifers; and GWFM: Groundwater from fractured media).

In approaches like DFN, discrete element method (DEM) and stochastic fracture models, when dealing with low-permeability media, impervious matrix is commonly assumed which reduces the fracture network to hydraulically connected pathways (Baghbanan and Jing, 2008; Long et al., 1982; Min et al., 2004; Rutqvist et al., 2013). However, doing so leads to inaccurate predictions of the pressure propagation through the fracture network (Lang et al., 2014; Taylor et al., 1999) as illustrated in Figure 3.10. Our results highlight further that even in extremely low-permeability rock matrix, leakage cannot be neglected and it starts to dominate since the early stages of injection (Figure 3.6). Therefore, the rock matrix permeability should be included in numerical models to reproduce leakage into the matrix and properly simulate the pressure diffusion through the fracture network in the subsurface applications in which leakage is non-negligible.

3.4.3 The origin of the leaky nature of fractures

The extremely low thickness of fractures plays a dominant role on the onset of leakage into the rock matrix after a short injection time, even for extremely low-permeability matrix. The assumption of impermeable confining layers of the Theis solution does not apply to fractures. The reason is that for a given layer with fixed permeability and porosity, but variable thickness, the transmissivity decreases with the layer thickness. Assuming a prescribed injection flow rate, pressure increases as the layer becomes thinner because pressure is inversely proportional to transmissivity, inducing a higher pressure gradient perpendicular to the interface between the injection and the confining layers (Figure 3.15a). Increasing the pressure gradient results in an enhanced leakage relative to the injection flow rate. Comparing a hectometer-thick aquifer with a micrometer-thick fracture, fracture transmissivity is 8 orders of magnitude smaller than that of the aquifer. Consequently, pressure buildup and, thus, the pressure gradient from the injection layer into the confining layer, is 8 orders of magnitude larger in the fracture than in the aquifer. This difference explains why the assumption of impervious confining layers applies for aquifers, but not for fractures.

To highlight the leaky nature of fractures even further, let us assume a prescribed injection pressure instead of a flow rate to impose the same vertical pressure gradient at the interface with the confining layers, and thus the leakage regardless of the layer thickness (Figure 3.15b). Let us consider two cases: a 100 m-thick aquifer and a fracture with an aperture of 10 μ m. To induce the same pressure build-up in both cases, the ratio of the flow rate to the transmissivity has to be maintained. Since the thicknesses differ by 7 orders of magnitude in the two cases, the injection flow rate into the fracture is 10⁷ times smaller than the injection flow rate in the thick aquifer. Given that the leakage flow rate is 10⁷ times lager for the fracture than for the thick aquifer. Consequently, leakage becomes non-negligible in fluid flow in fractured media.



Figure 3.15. Schematic representation of the different response to fluid injection of a thick layer (thickness in the 10² m scale) and a fracture (thickness in the 10⁻⁶ m scale) with the same permeability and porosity when (a) imposing the same injection flow rate and (b) prescribing the same injection pressure. In both cases, the ratio between the leakage into the low-permeability rock matrix and the injection flow rate is orders of magnitude larger for the fracture.

3.4.4 The role of fracture size

We have assumed an infinitely acting fracture, i.e., the pressure perturbation front does not reach the end of the fracture during injection. In real applications, it is likely that the length of fractures is finite and, thus, the tip is reached or that the fracture intersects other fractures, which would also affect the pressure evolution. For this reason, we analyze the pressure evolution in finite size fractures in which the tip is reached during injection (Figure 3.16). The early-time hydraulic behavior is the same for both finite and infinite fractures embedded in a low-permeability rock matrix. The pressure evolution is governed by leakage and the transition time between the two radial flow regimes (see Figure 3.11) is a function of the rock matrix permeability. However, when the pressure front reaches the fracture tip, the pressure build-up exhibits a steeper increase due to limited diffusivity and the pressurization changes from linear in log-scale to linear with time (Mathias et al., 2011; Q. Zhou et al., 2008). Noticeably, the shorter the fracture, the earlier the deviation occurs. The deviation time for the linear evolution of pressure as a function of the logarithm of time can provide information on the fracture length or the intersection with other fractures (Eq. (3.21)). Accounting for the proper pressure propagation evolution has implications, for instance, for induced seismicity forecasting, or for the design of hydraulic stimulation (a shorter duration than necessary may be chosen).



Figure 3.16 Dimensionless pressure evolution response to injection into a fracture surrounded by lowpermeability rock for an infinitely acting fracture (the black line) and two finite fractures (blue and red lines for dimensionless length of 500 and 200 respectively); Note that leakage occurs since very early time, and when the pressure perturbation front reaches the fracture tip, the pressure build-up increases dramatically.

3.5 Conclusion

We have investigated the hydraulic response of water injection into a fracture surrounded by low-permeability rock. The analysis of the pressure evolution reveals that leakage into the low-permeability rock matrix impacts fluid flow. The pressure evolution follows a straight line as a function of the logarithm of time whose slope corresponds to a transmissivity that is twice the actual one when injecting into a single fracture surrounded by low-permeability rock. This slope is reached within a few seconds after the start of injection. As a result, fractures should be considered as leaky rather than being surrounded by impermeable layers, even for very low-permeability rock matrix. The short transition time to leakage-dominated flow implies that field measurements may not show the initial transition prior to the stage in which leakage dominates. Furthermore, this leakagedominated regime can last for a long time (several days) in low permeable formations, which may lead to wrong interpretations of the pressure evolution if leakage is neglected. Overall, our findings reveal the leaky nature of fractures and have important implications for the interpretation of injection tests and modeling of fractured media because neglecting leakage overestimates fracture transmissivity and the pressure perturbation front.

4

Implicit hydro-mechanical representation of fractures using continuum approach

4.1 Introduction

Fractures are abundant in crystalline media. Either natural or engineered, fractures provide conductive pathways for mass and energy transport, supplying opportunities for exploitation of georesources, but also potential challenges for geo-engineering applications (Adler et al., 2013). For example, in Enhanced Geothermal Systems (EGS) or water resource exploration in fractured geological media (Berkowitz, 2002), fractures are the principal pathways for productivity (Goto et al., 2021; Olasolo et al., 2016; Parisio and Yoshioka, 2020). In contrast, permeability of fractures (if present) should be as low as possible in host rocks for nuclear waste disposal (Amann et al., 2018b; Xu et al., 2020) or cap rocks for geologic carbon storage (March et al., 2018; Vilarrasa et al., 2014, 2013b, 2013a). In geo-engineering applications, fractured porous media behave under complex and fully coupled (thermo-)hydromechanical processes. For instance, fractures intersected by or in the vicinity of the injection well may open as a result of pore pressure build-up causing permeability to increase, thus attenuating pressure build-up. Quantifying the dependence of fracture transmissivity on its aperture was the subject of some debate until Tsang (Tsang, 1992) settled it by distinguishing between hydraulic (cubic law, approximately the geometric mean aperture), mass balance (mean aperture) and viscous dissipation apertures as the equivalent apertures of a parallel plate fracture with the same flow, transport, and energy dissipation as the actual fracture with spatially variable aperture. The distinction is adequate for coupled problem and support using the cubic law, which has proven adequate for hard rocks (Dippenaar and Van Rooy, 2016; Guimerà and Carrera, 2000; Konzuk and Kueper, 2004; Witherspoon et al., 1980). This law implies a strong coupling of fluid flow and geomechanical response of the fractured media to fluid injection/production. The coupling may be further complicated by thermal effects caused by, e.g., the injection of cold water into a hot system, which not only contracts the rock but also modifies the density and viscosity of the fluid, and therefore, e. g., hydraulic conductivity (De Simone et al., 2013). The meaningful modeling of strongly coupled processes demands a cost-effective simplified yet accurate representation of the fractured medium.

The highly heterogeneous nature of fractured media, including complex networks of heterogeneous fractures (Meier et al., 2020), poses challenges to modeling approaches (Jin and Zoback, 2017) and calls for adequate representations of both matrix and fractures. One of the main challenges is to define and measure model parameters that allow the continuum scale modeling of scenarios in which fractures are either treated explicitly or considered implicitly within the porous medium itself. Explicit modeling comprises, amongst others (McLennan et al., 2010), techniques such as (1) Discrete Fracture Matrix (DFM), attempting to strike a balance between loss of accuracy by upscaling and geometric complexity (Alcolea et al., 2016; Flemisch et al., 2018; Jiang and Younis, 2017; Karimi-Fard et al., 2004; Martinez-Landa and Carrera, 2006), (2) Discrete Fracture Network (DFN), in which all fluid is assumed to be contained within the fracture network and the matrix is considered impermeable (Berrone et al., 2013; Fumagalli et al., 2019; Hyman et al., 2014; Li and Lee, 2008), and (3) Conduits (channels) Networks (CN) that represent fractured media as a network of 1D connected pipe-like elements forming a series of channels for fluid flow (Black and Barker, 2018; Cacas et al., 1990; Tsang et al., 1988). In a porous medium, the secondary permeability offered by a conductive fracture may yield an overall effective permeability much greater than the primary permeability provided by the connected pores (Neuzil and Tracy, 1981). As a result, flow occurs mainly along fractures and commonly leads to the assumption that the rock surrounding fractures is impermeable (Koudina et al., 1998; Long et al., 1982). However, this assumption generally may lead to inaccurate predictions of pressure changes. Instead, accounting for the flux between fractures and rock matrix (so-called leak-off (Geertsma and Haafkens, (1979)) improves the predictions (Lin and Yeh, 2021).

Both explicit and implicit approaches present advantages and disadvantages. Explicit approaches are simple and render enhanced accuracy in the representation of fractures. However, they entail complex geometries and high computational costs (Pandey et al., 2017; Salimzadeh et al., 2018; Watanabe et al., 2012). The conventional implicit approach, called the continuum method, includes both fractures and matrix in an equivalent porous medium. Transforming discrete fractures into continuum representations requires upscaling (Bonnet et al., 2001; Farmer, 2002; Gerritsen and Durlofsky, 2005; Lee et al., 2001; Renard and Ababou, 2022). Upscaling can be performed analytically or numerically. Analytical approaches (Liu et al., 2016; Oda, 1985) are generally based on geometry and/or flow features. Geometry-based upscaling approaches superimpose a grid onto the fracture network in which the corresponding fracture hydraulic conductivity (actually, any given property) is mapped on the grid formed by the intersections between fractures and the boundaries of the grid cells (Roubinet et al., 2010; Svensson, 2001). In flow-based upscaling, local steady-state solutions to the Laplace problem are usually employed to back-calculate effective permeabilities using Darcy's law (Durlofsky, 1991; Jackson et al., 2000; Oda, 1985; Sánchez-Vila et al., 1995). In numerical-based methods, representative sub-grid scale DFN simulations can be used to obtain upscaled relationships including elements of the permeability tensor (Bogdanov et al., 2003; T. Chen et al., 2018; Karimi-Fard and Durlofsky, 2016; Romano et al., 2020).

The most common implicit numerical approaches include Equivalent Porous Medium (EPM, also known as the single-continuum approach), Stochastic Continuum (SC), and Dual Continuum Medium (DCM). If fractures are not well connected, the EPM method may be employed to define grid block-scale effective properties describing the behavior of the entire fractured rock mass (Botros et al., 2008; Jackson et al., 2000; Sweeney et al., 2020). There are several flow-based upscaling procedures such as the numerical upscaling proposed by (Durlofsky, 1991) where equivalent grid-block permeabilities are computed by solving the fine scale pressure diffusion equation using effective medium theory representing fractures as thin ellipsoids embedded in a matrix (Sævik et al., 2014, 2013), and aggregation-based method (Hui et al., 2018). However, there is no separation of the characteristic lengths in the fractures and in the matrix. Hence, upscaling to the average characteristics often leads to low model accuracy, even from the conceptual standpoint. For example, the secondary permeability provided by conductive fractures often yields an average effective permeability several orders of magnitude larger than the primary permeability of connected pores in the matrix, which leads to a different and generally more clustered pore pressure distribution through the equivalent porous medium than the expected one (Zareidarmiyan et al., 2021). Therefore, EPM approaches fail to deliver reliable solutions whenever fracture spacing is in the order of the reservoir characteristic length (Zareidarmiyan et al., 2021).

SC approaches aim to develop equally-likely heterogeneous continua with stochastic representations of effective properties based on actual properties of the underlying fracture network (Neuman, 2005). The double or multi-continuum medium (DCM) approach is a preferable option among implicit approaches due to the more accurate representation of the embedding matrix. However, unconnected fractures can still communicate via the matrix (whose permeability is considered), making it difficult to identify hydraulic backbones (the dominating high transmissive structures) (Matthäi and Belayneh, 2004). In the presence of considerable matrix permeability, dual-permeability and dual-porosity models are advantageous as they represent fractures and matrix as separate continua that interact with each other through transfer functions. Dual-permeability models permit flow between matrix blocks, while dual-porosity models consider no communication between matrix blocks (Aguilar-López et al., 2020; Lemonnier and Bourbiaux, 2010; Warren and Root, 1963). Figure 4.1 shows a schematic of aforementioned methods and their relatively approximate accuracy versus each other and against the "true" fractured porous medium that is not possible to be fully characterized at all length scales (Neuman, 1990).

We introduce another implicit approach treating fractures as continuum layers, adjacent to the porous matrix, which are upscaled individually. This approach, termed Equivalent Fracture Layer (EFL), has the advantages of implicit (moderate computational cost), while displaying an accuracy similar to that of explicit methods (Figure 4.1). However, the question of how to choose the assigned properties of the continuum-equivalent individual fracture models to reproduce the behavior of discrete fractures remains open. Property assignment is a non-trivial problem aggravated by the large differences between fracture aperture (usually μ m to mm) and reservoir characteristic length (generally m to hm) (Andrés et al., 2021; Zareidarmiyan et al., 2020), which leads to a negligible fracture volume compared with the volume of the surrounding medium (Faybishenko et al., 2015). In fact, the lower-dimensional nature of fractures with an extreme area-aperture ratio poses a great challenge to numerical simulations (Lei et al., 2017; Thomas et al., 2020; Yoshioka et al., 2019) using either implicit or explicit representations of fractures (Berre et al., 2019; Lepillier et al., 2020).



Accuracy in background medium representation

Figure 4.1 Sketch comparing the accuracy of fractures and matrix modelling of different representation approaches. The suggested approach, EFL, (green frame) has the advantages of implicit approaches (blue) while generally yielding more accurate results like explicit approaches (red). Adapted from (Berre et al., 2019; Viswanathan et al., 2022)

Continuum methods are increasingly being combined with discrete fracture and matrix methods (DFM) (Ji et al., 2012; Joyce et al., 2014; Lee et al., 2001). Such approaches, familiarly known as hybrid methods, can incorporate diverse implicit-explicit method combinations. Several complex models coupling DFM and multi-continuum approaches have been developed, e.g., a dual-permeability hybrid model combining DFM and the dual-permeability model (Jiang and Younis, 2016). While complex hybrid models have demonstrated the capability of producing accurate results, the issue of expensive computational resources remains. Therefore, simpler hybrid models are preferred whenever they are applicable. The simplest hybrid model known as the single-porosity hybrid model can be considered a simplified DFM model with reduced complexity. This model explicitly represents large fractures in a fractured medium and represents small-scale fractures and the matrix using a single continuum known as a pseudo-matrix (Lee et al., 2001; Li and Lee, 2008; Rogers et al., 2007). To make this model a step simpler, the proposed method (EFL approach) can be used to upscale the explicitly represented fractures to an equivalent-continuum layer.

In this chapter, we propose a new EFL approach to accurately model not only fluid flow, but also the geomechanical response in fractures with arbitrary orientation, represented as equivalent continua at a numerically tractable scale (>> μ m). For illustration purposes, we focus on a single fracture embedded in low-permeability rock matrix, resulting in distinctive flow time scales. The manuscript presents first the methodology for calculating the equivalent hydromechanical properties of a fracture, analytically upscaled as a layer with a thickness much larger than the actual aperture. Second, we verify the procedure by considering fluid injection into a fracture embedded in a low-permeability rock matrix by comparing results of a finite element model including the real aperture (reference model) with those of models including the upscaled thicknesses of the equivalent fracture layer. Next, we validate the approach by comparing numerical results against field data acquired during a hydraulic stimulation at the Bedretto Underground Laboratory for Geosciences and Geoenergies in Switzerland. Finally, we discuss the implications of our findings to introduce another simple, yet, practical upscaling approach for fractured media.

4.2 Methodology

4.2.1 Governing equations

Transient fluid flow within a saturated fracture confined by a low-permeability rock matrix is governed by the flow equation (Bear, 1972)

$$\nabla \cdot (T\nabla h) = S \frac{\partial h}{\partial t} + r_s \tag{4.1}$$

where T [L²T⁻¹] is transmissivity, $h = p/\gamma_w + z$ [L] is hydraulic head, p is fluid pressure [ML⁻¹T⁻²], γ_w [ML⁻²T⁻²] is the specific weight of the fluid, z [L] is elevation from an arbitrary plane, S [-] is the storage coefficient, t [T] is time and r_s [ML⁻³T] is a sink/source term, including from/to the matrix, which can be important during transient periods even for low permeability matrix (See (Carrera and Martinez-Landa, 2000) for details). The mechanical process is solved by satisfying momentum balance that, neglecting inertial terms, reduces to the equilibrium of stresses

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{b} = \mathbf{0},\tag{4.2}$$

where σ [ML⁻¹T⁻²] is the total stress tensor and b [ML⁻²T⁻²] is the vector of body forces.

The relation between stress, strain, and pore pressure for isotropic materials within the linear elasticity theory for continuous media is given by Hooke's law

$$\Delta \boldsymbol{\sigma} = K \varepsilon_{\nu} \mathbf{I} + 2G \left(\boldsymbol{\varepsilon} - \frac{\varepsilon_{\nu}}{3} \mathbf{I} + \frac{\alpha}{2G} \Delta p \mathbf{I} \right), \tag{4.3}$$

where ε_{ν} [-] is the volumetric strain, ε [-] is the strain tensor, $K = E/(3(1-2\nu))$ [ML⁻¹T⁻²] is the bulk modulus, $G = E/(2(1+\nu))$ [ML⁻¹T⁻²] is the shear modulus, E [ML⁻¹T⁻²] is Young's modulus, ν [-] is the Poisson ratio, and α [-] is the Biot effective stress coefficient. In this work, we assume $\alpha = 1$, which leads to the strongest hydromechanical coupling (Zimmerman, 2000).

Equation (4.3) can be coupled with the flow equation through fluid pressure. Acknowledging that external loading and compressibility of the solid phase may affect water storage in the fracture, fluid mass conservation can be written as

$$\frac{\phi}{K_f}\frac{\partial p_f}{\partial t} + \frac{d}{dt}\left(\nabla \cdot \mathbf{u}\right) + \nabla \cdot \mathbf{q} = r_s,\tag{4.4}$$

where ϕ [-] is porosity, K_f [ML⁻¹T⁻²] is the fluid bulk modulus, u [L] is the displacement vector and q [L³T⁻¹] is the fluid flux, given by Darcy's law. Note that Equations (4.3) and (4.4) can also be coupled through the volumetric strain, which can be expressed as the divergence of the displacement vector.

4.2.2 The embedded model

Consider an open fracture with hydraulic aperture b_f [L]. Fracture permeability is assumed to be isotropic and given by $\mathbf{k} = k_f (\mathbf{I} - \mathbf{M})$ [L²], where \mathbf{I} [-] is the identity matrix, \mathbf{M} is the tensor of the fracture plane ($M_{ij} = m_i m_j$, where \mathbf{m} is the unit vector perpendicular to the fracture), and

$$k_f = \frac{b_f^3}{12a} \tag{4.5}$$

where a [L] denotes a somewhat arbitrary width for each fracture (strictly speaking the cubic law expresses the fracture permeability as $k_f = b_f^2/12$). When dealing with sets of parallel fractures, a is usually taken as the mean distance between fractures. Here, we seek an equivalent medium, so we take $a = b_f$ (Olsson and Barton, 2001). Equation (4.5) highlights the strong nonlinear relationship between fracture aperture and flow (Adler et al., 2013). Acknowledging the strain dependence of intrinsic permeability is needed for coupled modeling in fractured media (Olivella and Gens, 2005). Variable fracture permeability can be computed by taking into account that aperture changes are a function of volumetric strain as (Olivella and Alonso, 2008)

$$b_f = b_0 + (\varepsilon - \varepsilon_0)a \le b_{max},\tag{4.6}$$

$$k_f = k'_m + \frac{(b_0 + a\Delta\varepsilon)^3}{12a},$$
(4.7)

where k'_m [L²] is the intrinsic permeability of the matrix within the fracture layer, b_0 [L] and b_{max} [L] are the initial and maximum fracture aperture, $\Delta \varepsilon$ [-] is the volumetric strain change ($\Delta \varepsilon = \varepsilon - \varepsilon_0$), and ε_0 [-] is a threshold strain.

4.2.3 Equivalent hydromechanical properties of a fracture

Three entities play a role in the equations governing HM problems: flux, storage, and displacement. These which are controlled by transmissivity, storage coefficient, and stiffness, respectively. The adopted upscaled parameters of the equivalent fracture layer must represent the actual behavior of the real fracture (Figure 4.2). In other words, both the actual fracture and the equivalent fracture layer should have the same transmissivity, storativity, and stiffness, both initially and along its time evolution.



Figure 4.2 Concept of the equivalent fracture layer representing a real fracture

The transmissivity of a fracture is given by the product of hydraulic conductivity and aperture

$$T_f = \frac{\rho g}{\mu} k_f b_f = \frac{\rho g}{\mu} \frac{b_f^3}{12},$$
(4.8)

where ρ [ML⁻³] is fluid density, g [LT⁻²] is gravity, and μ [ML⁻¹T⁻¹] is fluid viscosity. The dependence of transmissivity on b_f^3 is the essence of the well-known cubic law (Brush and Thomson, 2003; Witherspoon et al., 1980; Zimmerman and Yeo, 2000) and expresses that fracture transmissivity is extremely sensitive to small changes in aperture. The Equivalent fracture layer with thickness of b_{eq} should carry the same flow rate as the actual fracture:

$$T_{eq} = T_f \to k_{eq} b_{eq} = k_f b_f, \tag{4.9}$$

where k_{eq} [L²] is the intrinsic permeability of the equivalent fracture layer. When equating the actual and upscaled fracture properties to represent the actual fracture aperture (b_f) by an equivalent continuum layer with a thickness b_{eq} , the upscaled equivalent hydromechanical fracture transmissivity, stiffness, and storativity become a function of the equivalency coefficient

$$\xi = \frac{b_f}{b_{eq}}.\tag{4.10}$$

To have the same transmissivity, equivalent parameters can be derived from equations (4.7) and (4.9) as

$$\dot{k_{meq}} = \xi \dot{k_{mf}}, \qquad b_{0eq} = b_{0f}, \qquad b_{max.eq} = b_{max.f}, \qquad a_{eq} = \frac{a_f}{\xi}, \qquad \varepsilon_{eq} = \xi \varepsilon_f, \quad (4.11)$$

where the subscript f and eq denote the properties of the fracture with its actual aperture and equivalent fracture layer, respectively.

The mechanical behavior of fractures can be characterized by normal and shear stiffnesses (Puig Damians et al., 2022; Yu et al., 2015)

$$\sigma_n = \lambda_n u_n, \qquad \tau_s = \lambda_s u_s \tag{4.12}$$

where σ_n [ML⁻¹T⁻²] and τ_s [ML⁻¹T⁻²] are normal and shear stresses, λ [ML⁻²T⁻²] is stiffness, and u [L] is displacement. The superscripts n and s denote normal and shear components, respectively. In general, one may expect λ_s to be itself a tensor, especially if the fracture is shear origin. In such case, irregularities tend to align with shear direction (orthogonal to the open channels), so that λ_s will be initially smaller in this direction. For the sake of simplicity and assuming that the impact of the initial irregularities diminishes as the fracture opens, we will assume scalar λ_s . Normal and shear stiffnesses of an arbitraryoriented fracture can be obtained as

$$\lambda_n = \frac{E_{of}}{b_f}, \qquad \lambda_s = \frac{G}{b_f}, \tag{4.13}$$

where E_{of} is an apparent oedometric modulus of the fracture. If the deformation out of the fracture plane is constrained, the modulus E_o is defined as

$$E_{of} = \frac{1 - \nu}{(1 + \nu)(1 - 2\nu)} E_f.$$
(4.14)

From equations (13) and (14), fracture stiffnesses can be determined as

$$\lambda_n = \frac{1 - \nu}{(1 + \nu)(1 - 2\nu)} \frac{E_f}{b_f}, \qquad \lambda_s = \frac{E_f}{2b_f(1 + \nu)}.$$
(4.15)

where E_f and ν are the apparent Young's modulus and Poisson ration of the fracture. Maintaining normal and shear stiffnesses, the equivalent Young's modulus and Poisson's ratio of the equivalent fracture layer can be obtained by

$$E_{eq} = \frac{3\lambda_n - 4\lambda_s}{\lambda_n - \lambda_s} k_s b_{eq}, \qquad v_{eq} = \frac{\lambda_n - 2\lambda_s}{2(\lambda_n - \lambda_s)}, \qquad \text{with } \lambda_n > 2\lambda_s. \tag{4.16}$$

In principle, the aperture and stiffness of the real fracture can be estimated (or measured) and, from them, the equivalent properties of the upscaled fracture can be easily calculated.

Finally, both layers should have same storativity as

$$S_{eq} = S_f \to S_{seq} b_{eq} = S_{sf} b_f, \tag{4.17}$$

where S_s [L⁻¹] is the specific storage (i.e., $\rho g(\phi \beta_w + \beta_x)$), β_w [M⁻¹LT²] is the compressibility of the fluid, and $\beta_x = 3(1-2\nu_x)/E_x$ [M⁻¹LT²] is the bulk compressibility of the layer x (either fracture (β_f) or equivalent layer (β_{eq})). Expanding the equation, we can calculate equivalent porosity as $\phi_{eq} = \xi \phi_f$.

4.3 Model verification and validation

4.3.1 A single fracture embedded in a low-permeability matrix4.3.1.1 Model setup

We numerically modeled a single circular fracture in which water is injected into its center through a well with radius r=0.1 m (Figure 4.3). As reference, we modeled the fracture with actual properties and compared results with implicitly upscaled models. The axisymmetric model represents a 100-m radius horizontal circular fracture with uniform thickness (10 µm as real aperture) embedded between two 10-m thick layers of lowpermeability rock at a depth of 1 km. The large radial extent of the fracture is such that the nature of the outer boundary, i.e., prescribed hydrostatic pressure or no flow, does not affect results during the injection. Both fracture and rock matrix continua have homogeneous and isotropic properties. Boundary conditions include zero horizontal displacement at both inner and outer lateral boundaries and zero vertical displacement at the bottom boundary. A constant flow rate $q=50 \text{ kg/s/m}^2$ is injected at the fracture segment of the inner boundary. A constant initial stress field ($\sigma_x=15$ MPa, $\sigma_y=25$ MPa, $\sigma_z=15$ MPa) and a linear hydrostatic pressure gradient (10 and 10.2 MPa at model top and bottom, respectively) were applied to the model. The fracture is assumed to be clean, i.e., actual porosity is set to 1, and its initial intrinsic permeability is calculated using equation (5) and assuming $a=b_f$, which results in $k_f = 8.33 \cdot 10^{-12} \text{ m}^2$. Input parameters for the matrix, fracture, and equivalent fracture layers are listed in Figure 4.3 and Table 4.1.

We built three additional models with increasing thickness of the equivalent fracture layer and applied the equivalent properties, i.e., permeability, porosity, and Young's modulus (Poisson's ratio is independent of the equivalent layer thickness) using the relationships derived in the section 2.3. A common structured finite element mesh consisting of 12,322 quadrilateral elements is used as spatial discretization for all models. The fracture consists of 5 rows of elements, whereas the matrix slabs contain 30 rows of elements in the vertical direction. The elements in the matrix are concentrated toward the fracture-matrix interfaces to capture the leak-off more accurately. Also, for the sake of accuracy, finite elements are concentrated towards the well to properly captured fluxes caused by injection and corresponding pressure variations in both fracture and matrix. We performed a mesh sensitivity analysis to ensure that further refinement does not affect the results, not displayed here for the sake of brevity. The models simulate water injection at a constant rate for 30 hours and are run twice, considering both constant and variable fracture permeability depending on deformation. We analyzed the pressure evolution at the injection well (r=0.1 m) and the hydromechanical response along the fracture at the end of the injection. The fully coupled hydromechanical numerical models were implemented using the finite element software Code Bright (Olivella et al., 1996, 1994).



Figure 4.3 Sketch of the axisymmetric model used for verification purposes: geometry, boundary, and initial conditions. Input parameters are indicated in the insets, where subscripts m and f denote matrix and fracture respectively (see also Table 4.1)

The injected volumetric flow rate into a fracture, Q [L³T⁻¹], must be conserved when upscaling fracture thickness with the equivalent fracture layer approach. Given that the flux injected into a layer through a fully penetrating well equals q = Q/A, where A [L²] is the cross-sectional area to flow, i.e., $2\pi r_w w$, r_w [L] being the radius of the well and w [L] the thickness through which fluid is injected, the equivalent injection flux into the equivalent fracture layer, is $q_{eq} = \xi q_f$ where $q_f = Q/(2\pi r_w b_f)$ is the injection flux for the actual fracture.

Table 4.1 Input parameters for the fracture and equivalent fracture layer models used for verification purposes

Fracture aperture (m)	$\xi = \frac{b_f}{b_{eq}}$	Fracture Permeability (m ²)	Porosity	Injection flux (kg/s)	Young´s modulus (MPa)			
Original frac	ture							
10-5	1	8.33·10 ⁻¹²	1	50	6.67			
equivalent fracture layer models								
0.001	10-2	8.33.10-14	10-2	0.5	667			
0.01	10-3	8.33.10-15	10-3	0.05	6670			
0.1	10-4	8.33·10 ⁻¹⁶	10-4	0.005	66700			

4.3.1.2 Numerical results

Both the pore pressure evolution at the injection well and the radial pressure distribution were reproduced accurately by the models with equivalent fracture layers compared to the reference model with explicit fracture representation (Figure 4.4). The pressure evolution curves (in Figure 4.4a) follow the typical Hantush leaky solution (Hantush, 1960, 1956). At beginning, after a short transition, it follows Theis solution (Theis, 1935) as storage in and leakage into the matrix are neglected, then during a transition period leak-off starts to play a role and decreases the pressure build-up. For the time scale of our analysis, i.e., 30 h, the low-permeability of the rock matrix does not allow the pressure evolution curve to reach to the fracture-matrix Theis solution (where both fracture and matrix act as a single system with steady state leakage and combined storage). Considering variable permeability decreases pressure build-up due to permeability enhancement since early times (less than a second) when volumetric strain starts to accumulate (Figure 4.4a, blue curves). Constant injection in the fracture forms a conical pressure profile versus radial distance (Figure 4.4b).



Figure 4.4 a) Pressure evolution at the injection well for reference models (actual fracture aperture; solid lines) and models with equivalent fracture layer for both constant (red lines) and variable (blue lines) permeability during constant flow injection; line styles correspond to different fracture apertures. b) Radial pressure profile along the horizontal mid-line of the fracture at the end of the injection (30 h)

Pressure build-up in the variable permeability model with $b_{eq}=10$ cm (blue dotted line in Figure 4.4a) starts to slightly deviate from the reference curve after ca. 2 hours of injection. This deviation is caused by more permeability enhancement ratio in that model compared to other models, which means transmissivity is no longer maintained constant for the upscaled model (Figure 4.5). In other words, the smaller is the equivalent aperture, the closer the model reproduces the reference case, as expected. This deviation could limit the upper bound of the upscaled aperture for an equivalent fracture layer since the coupled hydromechanical response not any more reflect the reference solution. However, models with 1 cm and 1 mm equivalent apertures yield well fitted results.



Figure 4.5 Transmissivity enhancement (a) and profile along the horizontal mid-line of the fracture at the end of the injection (30 h) (b) caused by accumulated deformation in the reference model (solid lines) and models with equivalent fracture layers (variable permeability cases). The magnitude orders of permeability are defined during upscaling, yet, the enhancement rates are similar in all models except b_{eq}=10 cm model which shows more enhancement

The embedded model employed here to account for variable permeability is a function of volumetric strain and discrepancy in models with larger equivalent aperture (i.e., 10 cm) stems from a different mechanical response of the fracture. Figure 4.6 shows stress profiles along the horizontal mid-line of the fracture, where lower compressive stresses are mobilized around the injection well at the end of the injection (30 h) for the thickest equivalent fracture layer. It is worth mentioning that the differences between the mechanical responses of the $b_{eq}=10$ cm models against the reference model are smaller in the variable permeability model because of the lower pressure build-up compared to the constant permeability models (Fogure 4.4a).



Figure 4.6 Profiles of stress components along the horizontal mid-line of the actual fracture and equivalent layers for both constant (red) and variable (blue) permeability models

Lower pressure build-up leads to smaller fracture opening in variable permeability models. Fracture layer apertures open around 3 and 2.2 µm for constant and variable permeability models, respectively (Figure 4.7; opening is calculated based on displacement difference of top and bottom of the fracture). Although $b_{eq}=10$ cm model reproduces the pressure evolution better in the constant permeability model in comparison to the variable permeability model (Figure 4.4a), it is less accurate in reproducing aperture enhancement in the constant permeability model. Note that the variable permeability models represent the actual fracture behavior more realistically than constant permeability models because fractures open in response to injection-induced overpressure, yielding significant permeability enhancement as a result of the cubic law (equation 4.5).



Figure 4.7 Fracture aperture change along the horizontal mid-line of the actual fracture (solid) for both constant (red) and variable (blue) permeability upscaled models in log-log and semi-log scales at the end of the injection (30 h). Aperture changes are calculated by displacement difference between top and bottom of the fractures

Vertical displacement at the top of the overlying rock layer in response to fluid injection presents a constant value until a radius of around 3 m and it follows a typical bell shape further away (Figure 4.8). The displacement in variable permeability models is lower due to the smaller pressure build-up (Figure 4.4b). The discrepancy of the $b_{eq}=10$ cm model compared with the reference solution is around 14% and it is related to differences in the fracture aperture changes (Figure 4.7).



Figure 4.8 Vertical displacement at the top boundary of the model versus radial distance at the end of the injection (30 h)

4.3.2 Bedretto experiment 4.3.2.1 Model setup

We validated our upscaling approach of implicitly representing fractures with an equivalent fracture layer by comparing numerical results with field data acquired during the hydraulic stimulation of a fracture at the Bedretto Underground Laboratory for (BULGG; see more Geosciences and Geoenergies detailed information in http://www.bedrettolab.ethz.ch). BULGG enables medium- to large-scale in-situ experiments with a focus on hydraulic stimulation and fault reactivation (Figure 4.9). The overburden directly above the laboratory is approximately 1500 m, providing conditions that start to resemble realistic EGS systems (scale 1:3 approximately) (Meier et al., 2020, 2022). To characterize the rock mass, several boreholes were drilled perpendicular to the tunnel axis with lengths ranging from 100 m to 400 m MD (Measured Depth; Figure 4.9c). A large number of hydraulic stimulation tests have been and are being performed at BULGG to stimulate the intersected fractures (Meier et al., 2022). Based on stress measurements (Bröker and Ma, 2022), BULGG is in a normal faulting and/or strike-slip stress regime, and the rock mass is close to be critically stressed (David et al., 2020; Gischig et al., 2020; Ma et al., 2019).



Figure 4.9 a) Location and trace of the Bedretto gallery excavated in Rotondo granite in Switzerland. b) Cross-sectional view of the Bedretto lab through the tunnel (Ma et al., 2022; Shakas et al., 2020). c) Configuration of the MB1, MB2 and MB3 boreholes with respect to the Bedretto Tunnel. Fractures and fault zones, mapped along the tunnel and intersected by the boreholes, are colored according to fracture strike

We developed a 2D plane-strain numerical model to simulate the hydraulic stimulation in Bedretto. It comprises an inclined plane dipping (on average) 42° downwards following the trajectory of the boreholes and has a large extension covering around 75 km² of the site (Figure 4.10a). The Bedretto gallery is located at the center of the upper boundary of the model (Figure 4.10b) and the bottom boundary is at a true vertical depth of 5000 m (-7472.4 m in the inclined model). The model comprises the main characterization boreholes (MB1 to MB4) and the two main stimulation boreholes (ST1 and ST2) as well as the major fracture and shear zones identified through borehole logging and geological structural analysis (Ma et al., 2022; Meier et al., 2020). We used an unstructured mesh that consists of 27,248 quadrilateral elements and 27,420 nodes and is highly refined at the closest vicinity of the model are fixed against lateral and vertical displacements, respectively. A linear distributed fluid pressure and initial stresses are applied to the model from top to bottom (Figure 4.10a).



Figure 4.10 a) Model geometry, boundary and initial conditions, and state of stress at top and bottom boundaries. b) Configuration of wellbores and the identified fracture/shear zones within the model. c) Detailed view around the stimulated fracture (in red). d) Mesh configuration of the same detailed view

Fractures are modeled as an elastic continuum medium with homogeneous hydromechanical properties. We used the embedded model to compute fracture
permeability changes according to Equation (4.7). As a result, fracture permeability varies with distance from the injection well, being largest near the well and approaching the initial value further away from the pressurization front, where the fracture has not undergone overpressure-induced opening. Table 4.2 lists the equivalent parameters of the stimulated fracture and rock matrix properties used in the numerical simulation. The modeling sequence includes the tunnel drainage effect on pore pressure during and after excavation and the subsequent consolidation covering 40 years (since the end of the tunnel excavation). The injection interval is within borehole MB1 (Figure 4.10c), in which water is injected through an isolated section into the fracture at a measured depth of 267 m (true vertical depth 188.8 m)

Table 4.2 Input parameters for rock matrix and equivalent fracture layer

	E (GPa)	ν	ϕ .	<i>k</i> (m ²)			
				k_m (m ²)	$b_{\theta}(\mathbf{m})$	<i>a</i> (m)	$\boldsymbol{b}_{max}\left(\mathbf{m}\right)$
Fracture (equivalent)	23	0.37	0.005	5×10 ⁻¹⁷	2.25×10 ⁻⁶	0.01	1.34×10 ⁻⁴
Rock matrix	46	0.37	0.005	2.5×10 ⁻¹⁸			

4.3.2.2 Simulation of the field injection experiment

The numerical simulation covers the first 40 minutes of the field experiment, which overall lasted 8 hours). Figure 4.11 compares the temporal evolution of the generated overpressure at the injection interval predicted by the numerical model against the experimental data. The model accurately reproduces field measurements, with a small discrepancy at the beginning of each injection steps, which attribute to non-modelled equipment compliance effects. Despite these small deviations, (1) simulated and measured trends are very similar, and (2) simulated injection pressure fits well the field data from the mid-times of each injection step.



Figure 4.11 Pressure evolution at the injection interval reproduced by the numerical model (red line) against injection pressure measured at the field (black line) as well as fluid injection rate (blue line)

The embedded model used in this simulation enhances permeability of the fracture in the vicinity of the injection interval (around 6 m) after 40 min of injection (Figure 4.12). Note that the behavior of the fracture is assumed to be elastic and the permeability enhancement in the embedded model is based on elastic strains only. Permeability linearly increased around 7% at a point near the injection interval after 40 min of injection which was not enough to reach the jacking pressure. Notably in the vicinity of ST2 well the permeability of the fracture has a spike governed by the permeability of the well.



Figure 4.12 Permeability profile in the middle of the fracture (d is the distance along the middle of the fracture) at the end of the injection period (t=0.7 h) in both sides of the injection interval (located at d=0); In the inset: permeability evolution at a point near the injection interval.

4.4 Discussion

Numerical modeling of fractured media faces the major challenge of very different spatial scales of fractures and matrix, which lead to very different flow characteristic times. In a kilometer-scale reservoir problem, it is difficult to express the micrometer aperture of actual fractures using a 1:1-scale element. We show that a viable approach is to upscale the fracture thickness while maintaining fracture transmissivity, storage coefficient and stiffness to preserve flow and deformation. The equivalent properties through an adequate upscaling for representing fractures (section 4.2.3) provide an approach to employ a layer with a thickness several orders of magnitude larger than the actual fracture aperture, thus alleviating discretization issues whilst reproducing the behavior of the actual fracture with accuracy.

Simulation results show that there is an upper bound for the validity of the suggested upscaling approach. Although the model with $b_{eq}=10$ cm yields accurate results for hydraulic analysis (Figure 4.4), the hydromechanical response is not as accurate as models with thinner apertures (Figures 4.5-4.7). It is worth mentioning that, during upscaling of Young's modulus, we have noticed that when E_{eq} exceeds Young's modulus of rock matrix (E_m) , the results become unreliable. For instance, the upscaled equivalent modulus is $E_{eq}=66$ GPa (for $b_{eq}=10$ cm model) and we had to set $E_m=70$ GPa to have a reliable result. This is another limiting upper bound factor for the proposed approach. However, using $b_{eq}=1$ cm provides the required accuracy as well as a convenient discretization process.

Suffice to say that the closer is the equivalent aperture to the actual one, the better is the accuracy as expected, especially in the mechanical response. However, differentiating between $b_{eq}=1$ cm and $b_{eq}=1$ mm models is difficult and the results are almost the same. This reinforces the applicability of the methodology, since we get what we expected. Furthermore, the method can be applied to any geometry of the fracture and with multiple fractures, as we have applied to a complex fracture network like Bedretto experiment.

Preferably, fully-explicit fracture network representation employing DFM methods would circumvent any error arising from upscaling procedures (Garipov and Hui, 2019). However, limitations on computational resources entail the use of continuum methods in conjunction with DFM methods. For a porous medium in which the properties of fracture networks vary between zones, different models might be employed in each zone to diminish the total required computational expenses. Our proposed approach validated by reproducing the field experiment result at Bedretto presents a simple, yet, effective method to utilize in the modeling of fractured media.

4.5 Conclusion

We have derived equivalent hydromechanical properties for an equivalent-continuum layer that is several orders of magnitude thicker than the represented fracture. We have obtained identical simulation results for equivalent fracture layers represented with cmscale thickness as the actual fracture aperture (which is in the μ m scale). Employing this method, the discretization of fractures is much more tractable while the accuracy is maintained. Much remains to be done such as applying the method to complex fracture networks, still, we have validated the upscaling approach by reproducing a field experiment of water injection into a fracture at Bedretto. Thus, the equivalent fracture layer approach represents a useful method to model geo-energy and geo-engineering applications in fractured media involving scales differing several orders of magnitude to handle discretization problem.

5

NUMERICAL MODELING OF HYDRAULIC STIMULATION OF FRACTURED CRYSTALLINE ROCK AT THE BEDRETTO UNDERGROUND LABORATORY

5.1 Introduction

A global trend towards CO_2 and nuclear-free technologies has promoted interest in deep geothermal energy as an alternative renewable source, free from seasonal fluctuations and, thus, with a potential for continuous energy output (Pruess, 2006; Randolph and Saar, 2011). Geothermal energy production has been successful in locations with favorable geological conditions such as volcanic fields, hydrothermally active areas, or sedimentary basins with deep-seated permeable rock formations. Enhanced (or Engineered) Geothermal Systems (EGS), previously referred to as Hot Dry Rock or Petrothermal Systems, are envisioned as a way to tap heat from any place in the territory (Brown et al., 2012; Olasolo et al., 2016).

The goal of EGS is the exploitation of regions with relatively high geothermal gradients through the creation (hydrofracturing) or reactivation (hydroshearing) of a fracture network of sufficient permeability to enable fluid circulation (Baria et al., 1999; Breede et al., 2013; Gan and Elsworth, 2014; Pine and Batchelor, 1984). The temperature necessary to produce electricity, i.e., >150 $^{\text{o}}$ C, is found at depths greater than 4-6 km, which is typically within the crystalline basement. The crystalline basement is assumed to be critically stressed (Townend and Zoback, 2000). Therefore, fluid injection concerns not only rock mass permeability, but also crustal strength and deformability, and

ultimately fault instability and induced seismicity (Achtziger-Zupančič et al., 2017; Ingebritsen and Manning, 2010; Manga et al., 2012).

To enhance permeability, injection-induced shear slip and dilation of preexisting fractures have been recognized as the most promising approach for extracting geothermal energy from hot ultralow-permeability rocks at depth (Riahi and Damjanac, 2013; Ye and Ghassemi, 2018). Shear reactivation of fractures/faults caused by pressurized fluid injection is of utmost importance in many subsurface engineering problems and reservoir stimulation (Rutqvist et al., 2007; Safari and Ghassemi, 2015; Vilarrasa et al., 2021), particularly with regard to induced microseismicity (Ellsworth, 2013; Evans et al., 2005; Guglielmi et al., 2015a; Kim, 2013; Majer et al., 2007; Safari and Ghassemi, 2016; Vilarrasa et al., 2019). It is referred to as shear stimulation or hydroshearing in EGS in which, contrary to the hydrofracturing process (which involves short-duration high-pressure injection and proppant usage), the injection pressure aims at causing shear slip and dilation of existing rough fractures (Mallikamas and Rajaram, 2005; Vilarrasa et al., 2011). This fracture self-propping by asperities is considered an effective means of permanently enhancing permeability (Kc and Ghazanfari, 2021; Meng et al., 2022). Furthermore, new cracks can be created because shear slip increases the stress intensity at the tips of preexisting fractures, potentially leading to fracture propagation and/or generating fracture networks (Bunger et al., 2013; Evans et al., 2005; Rahman et al., 2002; Willis-Richards et al., 1996). The main challenge is to develop adequate permeability in the reservoir while retaining sufficient heat transfer area and keeping the magnitude of induced seismicity as low as possible during reservoir stimulation (Grigoli et al., 2017; Kraft et al., 2009; Majer et al., 2007). Understanding the governing processes is of utmost importance to improve, and ultimately standardize, the applicability of EGS shear stimulation (Kumari and Ranjith, 2019).

Although the process of shear stimulation is theoretically well understood and routinely modelled, fundamental investigations through laboratory tests and field measurements have been limited. Laboratory-scale experiments can provide an understanding of coupled processes pertinent to the shear stimulation but suffer from test conditions as well as scalability that might lead to oversimplistic fracture flow that is not representative of a heterogeneous rock mass. (Guglielmi et al., 2015a, 2015b) completed two mesoscale reactivation tests by injecting high-pressure fluid into carbonate and shale faults. One of the insights achieved from these in situ reactivation tests is that aseismic/seismic shear slip by fluid injection enhanced the conductivity of the faults. Another intermediate-scale hydro-shearing experiment was executed in the naturally fractured and faulted crystalline rock mass at the Grimsel Test Site (Switzerland) in 2017 (Amann et al., 2018a; David et al., 2018a, 2018b). One of the key findings of this experiment is that initially low-transmissivity structures were stimulated more productively compared with structures of higher initial transmissivity. However, these field tests were conducted on faults and fractured zones at a relatively shallow depth (<600 m), i.e., in rocks with relatively low confinement and low enthalpy potential.

Considering the necessity of an experiment with a more similar condition to intermediate and high enthalpy geothermal systems, the Bedretto Underground Laboratory for Geosciences and Geoenergies (BULGG) hosts medium to large-scale insitu experiments with a focus on hydraulic stimulation and fault reactivation and associated induced seismicity (Figure 5.1). These experiments aim at developing effective and safe hydraulic stimulation protocols to enhance permeability at a controlled risk of induced seismicity for creating an EGS. The overburden directly above the laboratory is approximately 1500 m, providing conditions that start to resemble realistic EGS systems (scale 1:3 approximately) (Meier et al., 2020, 2022). To characterize the rock mass, several boreholes were drilled perpendicular to the tunnel axis with lengths ranging from 100 m to 400 m MD (Measured Depth). An additional set of short 30-40 m-long vertical boreholes were drilled, for conducting mini-frac tests aimed at quantifying the local state of stress (Bröker and Ma, 2022). A suite of hydraulic stimulation tests has been performed at the BULGG to stimulate the fractures intersected by the long boreholes MB1, ST1 and ST2 (Figure 5.1). Stress measurements by hydraulic fracturing technique indicate that the BULGG is in a normal faulting - strike-slip stress regime and that the rock mass is close to critically-stressed (Bröker and Ma, 2022; David et al., 2020; Gischig et al., 2020; Ma et al., 2022, 2019).



Figure 5.1 a) Top view of the Bedretto gallery and the hosting Rotondo granite; b) SE to NW crosssectional view of the Bedretto lab; c) 3D view of the longest boreholes. Adapted from (Ma et al., 2022; Shakas et al., 2020).

This chapter aims at numerically modeling and analyzing the hydraulic stimulation performed in borehole MB1 (in blue in Figure 5.1c) at the BULGG in February 2020. Numerical simulation is an essential method to investigate coupled hydromechanical processes and to better understand the fundamental mechanisms and feedbacks that occur in geothermal reservoirs. This understanding is particularly important due to the coupling of permeability and fracture aperture (Taron and Elsworth, 2009). I present three numerical models with increasing complexity (in terms of material constitutive law and coupling of permeability and fracture aperture), which we find to get progressively closer to the conceptual model representing the behavior of the system. Then, I compare numerical results with field experiment data and discuss the implications. Based on the best model, I extend our analysis to poromechanical processes occurring during the stimulation and discuss our findings. Simulation results reveal the extent of the stimulated fracture and permanent permeability enhancement and show that hydroshearing in the stimulated fracture has a non-negligible impact on the stability of adjacent joints due to stress redistribution, which may affect their subsequent stimulation.

5.2 Methodology

5.2.1 Numerical models

The numerical model is a 2D plane-strain inclined plane that contains the boreholes that, on average, dip 42° downwards to the southwest (Figure 5.1). The model is refined at its center, which represents the BULGG and its vicinity, and grows to a large extension (75 km²; Figure 5.2), beyond the whole Bedretto gallery (top center of the model) to avoid spurious boundary effects. For similar reasons, the bottom boundary is at a true vertical depth of 5000 m (y=-7472.4 m in the inclined plane). Both sides and the bottom of the model are fixed against lateral and vertical displacements, respectively. A linear distributed fluid pressure and initial stresses are applied to the model from top to bottom (Figure 5.2a). The major fractures and shear zones identified through borehole logging and geological structural analysis are included in the model (Ma et al., 2022; Meier et al., 2020). The fractures have been modeled as upscaled elastic continuum media with different hydromechanical properties but homogeneous in their space. The mesh also includes the main boreholes (MB1 to MB4, ST1, and ST2 with 20 cm thickness) and is highly refined at the closest vicinity of the modeled fractures and the boreholes. Overall, the mesh consists of 27,248 quadrilateral elements with corresponding 27,420 nodes (Figure 5.2d).





Figure 5.2 a) Model geometry and boundary conditions; b) Configuration of boreholes, identified fractures and fault zones; c) Detailed view around the stimulated fracture (in red); d) Mesh configuration from global to detailed view around the stimulated fracture zone.

Three models were built on this setting. In the first model (termed here model EP, for "Elastic Prescribed transmissivity") the permeability of the main fracture crossing the injection interval (in red in Figure 5.2c) has been assigned (homogeneous all along the fracture, but variable in time) to achieve a reasonable fit of the measured pressure evolution at the injection interval. However, changes in fracture aperture occur mainly in the vicinity of the injection interval as a result of injection-induced overpressures. Hence, the second model (model EE, "Elastic Embedded") incorporates the "embedded model", in which permeability is a function of volumetric strain described in section 5.2.4. In this second model, fracture permeability varies with distance from the injection interval and remains constant and equal to the initial value far away from it, where pressurization has not dilated the fracture. While this approach allows obtaining a good reproduction of the measured injection pressure at early stages, it fails to provide a good fit once the fracture reactivates and inelastic strains occur. Thus, to account for permeability enhancement induced by dilatancy due to the shear slip of the fracture, the third model (model VE) incorporates a viscoplastic constitutive law that includes dilatancy and strength softening. Table 5.1 summarizes the main input values for these models and the host rock. Notably, each fracture has different hydraulic and mechanical properties inferred from well logging and hydraulic tests. However, variable permeability is considered only in the stimulated fracture because the main impact at the surrounding fractures is mainly poroelastic but not hydraulic. The hydraulic and mechanical parameters of the surrounding fractures are not relevant to system changes induced by injection, which are mainly local and driven by the parameters of the stimulated fracture and surrounding matrix. The fully coupled hydromechanical numerical models are implemented using the software CODE_BRIGHT (Olivella et al., 1996, 1994).

Table 5.1 Hydromechanical properties of the rock matrix (granite) and the stimulated fracture for different tested models

		Stimulated fracture				
	Granite	EP	EE	VE		
Mechanical constitutive behavior	Elastic	Elastic		Viscoplastic		
Permeability (k)	$2.5 \times 10^{-18} \text{ m}^2$	Prescribed Embedded model				
Young's modulus (E)	46 GPa	23 GPa				
Poisson ratio (ν)	0.37	0.37				
Porosity (φ)	0.005	0.005				
Viscosity (µ)	-	-	-	2.5 GPa·s		
Peak friction angle (φ_{peak})	-	-	-	23°		
Residual friction angle (ϕ_{res})				20°		
Cohesion (c)	-	-	-	0.01 MPa		
Dilatancy angle (ψ)	-	-	-	20°		
Critical value of the softening parameter (η^*)	-	-	-	0.001		

The models are initialized by simulating the drainage effect of the tunnel on porewater pressure by imposing atmospheric pressure at the top boundary, and the subsequent consolidation, which tends to close fractures. The drainage period spans from the end of the excavation in 1976 until now. As such, the initial decompression of the system caused by excavation is not considered because its transient effects are small, as shown in a prior sensitivity analysis. In the same line of arguments, the drilling of boreholes is not modelled explicitly. Subsequently, the stimulation test (the first one in a series of many at the BULGG) is modeled by injecting water through an isolated section of borehole MB1, at a measured depth of 267 m (true vertical depth 188.8 m), into the fracture (in red in Figure 5.2c). Isolation was achieved by a double packer, also included in the model as a very stiff and low-permeability section of the borehole (E=4600 GPa, $k=2.5\times10^{-18}$ m², after inflation). The permeability of the boreholes, also modelled explicitly, is 2.5×10^{-14} m². The numerical simulations cover the first 3.4 hours of the field experiment, during which we compare the outcomes of the three models with the experimental results. Results of model VE are extended in time up to the first 8 hours of the experiment.

5.2.2 Governing equations

The mechanical problem is solved by satisfying the momentum balance. Neglecting inertial terms, the momentum balance reduces to the equilibrium of stresses,

$$\nabla \cdot \boldsymbol{\sigma} + \boldsymbol{b} = \boldsymbol{0} \tag{5.1}$$

where σ [ML⁻¹T⁻²] is the total stress tensor and b [ML⁻²T⁻²] is the vector of body forces.

In linear elasticity theory for continuous media, the relationship between stress, strain, and fluid pressure for isotropic materials is given by Hooke's law,

$$\Delta \boldsymbol{\sigma} = K \varepsilon_{\nu} \boldsymbol{I} + 2G \left(\boldsymbol{\varepsilon} - \frac{\varepsilon_{\nu}}{3} \boldsymbol{I} + \frac{\alpha}{2G} \Delta p_{f} \boldsymbol{I} \right), \qquad (5.2)$$

where ε_{ν} [-] is volumetric strain, **I** [-] is the identity matrix, ε [-] is the strain tensor, $K = E/(3(1-2\nu))$ [ML⁻¹T⁻²] is the bulk modulus, $G = E/(2(1+\nu))$ [ML⁻¹T⁻²] is the shear modulus, E [ML⁻¹T⁻²] is Young's modulus, ν [-] is the Poisson ratio, p_f [ML⁻¹T⁻²] is fluid pressure, and α [-] is the Biot effective stress coefficient. In this work, I assume $\alpha =$ 1, which leads to the strongest hydromechanical coupling (Zimmerman, 2000).

Equation (5.2) is coupled with the flow equation through fluid pressure. Assuming that there is no external loading and neglecting the compressibility of the solid phase, fluid mass conservation can be written as

$$\frac{\Phi}{K_f}\frac{\partial p_f}{\partial t} + \frac{d}{dt}(\nabla \cdot \boldsymbol{u}) + \nabla \cdot \boldsymbol{q} = 0,$$
(5.3)

where $\boldsymbol{\Phi}$ [-] is porosity, K_f [ML⁻¹T⁻²] is water bulk modulus, t [T] is time, u [L] is the displacement vector, q [L³T⁻¹] is the water flux, given by Darcy's law, and d/dt denotes material derivative. Note that the flow (Eq. (5.3)) and mechanical (Eq. (5.2)) equations can be also coupled through the volumetric strain (second term in the left-hand side of Eq. (5.3)), which can be expressed as the divergence of the displacement vector.

5.2.3 Fracture constitutive model

Fracture reactivation is modeled by a viscoplastic constitutive law in which fracture failure is given by the Mohr-Coulomb criterion and includes dilatancy and strain softening. The yield function (F) and the flow rule (G) are defined as

$$F = p \cdot \sin \varphi(\eta) + \left[\cos \theta - \frac{1}{\sqrt{3}} \sin \theta \cdot \sin \varphi(\eta) \right] \cdot \sqrt{J_2} - c(\eta) \cdot \cos \varphi(\eta), \quad (5.4)$$

$$G = \xi \cdot p \cdot \sin \psi + \left(\cos \theta - \frac{1}{\sqrt{3}} \sin \theta \cdot \sin \psi\right) \cdot \sqrt{J_2} - c(\eta) \cdot \cos \varphi(\eta), \qquad 5. (5)$$

where p [ML⁻¹T⁻²] is the mean stress, J_2 [ML⁻¹T⁻²] is the second invariant of the deviatoric stress tensor, η [-] is the softening parameter, ξ [-] is a parameter for the plastic potential, φ [°] is the friction angle, c [ML⁻¹T⁻²] is cohesion, and ψ [°] is the dilatancy angle. The invariant θ [°] (Lode's angle) is defined as

$$\theta = \frac{1}{3} \sin^{-1} \left(-\frac{3\sqrt{3}}{2} \frac{J_3}{J_2^{3/2}} \right), \quad -30^\circ \le \theta \le 30^\circ, \tag{5.6}$$

where J_3 [ML⁻¹T⁻²] is the third invariant of the deviatoric stress tensor. The stress function T(F) is

$$T(F) = F^m \text{ for } F \ge 0, \ T(F) = 0 \text{ for } F < 0,$$
 (5.7)

where m [-] is a constant power, chosen equal to 3 here (Vilarrasa et al., 2010). Both the cohesion and the friction angle can depend on the softening parameter (η) as

$$\lambda(\eta) = \begin{cases} \lambda^{peak} & \eta \leq 0\\ \lambda^{peak} + \left(\frac{\lambda^{res} - \lambda^{peak}}{\eta^*}\right) \cdot \eta & 0 \leq \eta \leq \eta^* ,\\ \lambda^{res} & \eta^* \leq \eta \end{cases}$$
(5.8)

where λ represents either cohesion (c) or friction angle (φ), and λ^{peak} and λ^{res} are user defined peak and residual values, respectively (see Table 5.1). As shown in Table 5.1, cohesion is low and we assume a constant value equal to 0.01 MPa. η^* is the value of the softening parameter controlling the transition between the softening and residual stages. The softening parameter depends on plastic strain as

$$\eta = \sqrt{\frac{3}{2}} \cdot \left[\left(\varepsilon_x^p - \varepsilon_m^p \right)^2 + \left(\varepsilon_y^p - \varepsilon_m^p \right)^2 + \left(\varepsilon_z^p - \varepsilon_m^p \right)^2 + \left(\frac{1}{2} \gamma_{xy}^p \right)^2 + \left(\frac{1}{2} \gamma_{yz}^p \right)^2 + \left(\frac{1}{2} \gamma_{zx}^p \right)^2 \right], \quad (5.9)$$

where $\varepsilon_m^p = \frac{1}{3}(\varepsilon_x^p + \varepsilon_y^p + \varepsilon_z^p)$ [-] is the mean plastic strain, and ε and γ are the diagonal and off-diagonal terms of the plastic strain tensor.

The quantification of shear slip tendency and proximity to shear failure conditions can be calculated with the mobilized friction angle. Shear failure occurs when the mobilized friction angle equals the actual friction angle. An alternative means of representing mobilized friction resistance, without implying a specific spatial orientation, involves expressing it in terms of invariants of the effective stress tensor. Considering the mean effective stress p' and deviatoric stress q, the mobilized friction angle can be expressed as

$$\varphi_{mob} = \sin^{-1} \left(\frac{3M}{6+M} \right), \tag{5.10}$$

where $M = \frac{q}{p'}$ is the slope of the stress path curve in the p'-q diagram.

5.2.4 The embedded model

The modelled fracture was identified in the lithological and image logs and in cores retrieved during the drilling of borehole MB1. This zone is a composite of several smaller fractures embedded in a matrix material. The permeability of the stimulated fractured zone is computed using the cubic law (Witherspoon et al., 1980), which makes fracture transmissivity proportional to b^3 (*b* being the aperture). Since CODE_BRIGHT adopts a small displacements approach, the geometrical grid aperture is fixed. Therefore, actual aperture changes, which are proportional to volumetric strain, are modeled by changing permeability as

$$k = k_m + \frac{(b_0 + a\Delta\varepsilon)^3}{12a},\tag{5.11}$$

where k_m [L²] is the intrinsic permeability of the matrix within the fracture zone (in red in Figure 5.2c), a [L] is the spacing between the fractures within the fracture zone, b_0 [L] is the initial fracture aperture, $\Delta \varepsilon$ [-] is the volumetric strain change ($\Delta \varepsilon = \varepsilon - \varepsilon_0$), and ε_0 [-] is a threshold value. For the stimulated fracture zone, the following parameters are considered: $k_m = 5 \cdot 10^{-17} \text{ m}^2$, i.e., 20 times larger than that of surrounding granite, $b_0 =$

 $2.25\cdot 10^{-6}\,\mathrm{m}$, $a=0.01\,\mathrm{m},$ and $b_{max}=1.34\cdot 10^{-4}\,\mathrm{m},$ which is the maximum aperture (upper bound of aperture), above which fracture permeability stops increasing.

5.3 Results

5.3.1 Reproduction of measured injection pressures

In the EP model, the temporal evolution of the permeability of the stimulated fracture is manually adjusted as constant during each injection interval so as to reproduce the observed injection pressure each interval. Although the overall model fit is good up to 2.5 h of injection (green dotted line in Figure 5.3a), it fails to reproduce the shape of the pressure curve in each injection step, in which pressure sharply increases at the beginning and the subsequent pressure build-up diminishes smoothly with time under constant flow rate (note that the first steps, until t~1.3h were intended to be constant pressure head tests). In short, the EP model fits well the beginning and end pressures for each step, but not the intermediate evolution. As discussed below, this discrepancy reflects that permeability changes are imposed for the whole fracture and not just for the actually stimulated region, which results in an unrealistic rapid pressure propagation along the whole fracture (Figure 5.4a).

The EE model (Eq. 5.10) accounts for both the spatial and temporal evolutions of fracture transmissivity in response to deformation. The brown curve in Figure 5.3a depicts the temporal evolution of generated overpressure at the injection interval predicted by the model with variable permeability as a function of fracture aperture (EE model). This model can accurately reproduce the field test results until 0.7 h. We attribute subsequent discrepancies to fracture dilatancy caused by shear slip, which leads to an additional, and irreversible, permeability enhancement. The elastic nature of this model cannot reflect this irreversible hydromechanical response. Consequently, the generated strain is smaller than the actual one, and the embedded model EE yields less permeability enhancement than the actual one. As a result, the calculated overpressure is higher than the measured one at late times, when shear slip has become significant. This limitation is overcome by the VE model.



Figure 5.3 a) Temporal evolution of calculated and measured overpressure (i.e., above formation pressure) at the injection borehole; b) Temporal evolution of fracture permeability in models with prescribed and variable permeability near the injection interval (point 1 in Figure 5.6c) and timestamps of observed induced microseismic events.

Figure 5.3b displays the temporal evolution of permeability prescribed (model EP) or calculated (models EE and VE). As observed in Figure 5.3a, all models render more or less a good fit with the generated overpressure until around 0.7 h, when the jacking pressure is achieved and the initially tight fracture gets opened, which leads to (1) the first sudden pressure drop under constant flow rate (Figure 5.3a), and (2) the corresponding sudden permeability increase (Figure 5.3b). The sudden increases in storage capacity and permeability hindered the control of pressure, which tended to drop. Therefore, the injection protocol was changed to constant flow rate injection at 1.3 h. A first shut-in at t=1.5 h led to a sudden drop of fracture permeability. Notably, the permeability drop required by the EP model to still reproduce the measured injection pressure is way larger than those calculated by the EE and VE models, what confirms the need to accommodate spatial variability in permeability enhancement. During the two additional shut-in episodes until t=3.4 h, the EE model shows a severe permeability reduction compared to the VE model, which reveals the need to accommodate permanent enhancement of fracture permeability.

The VE model reproduces the temporal evolution of injection overpressure better than previous models, especially during the last injection phase (t > 2.5 h). The VE model allows to simulate fracture reactivation and yields an additional and permanent permeability enhancement when compared with the elastic models EP and EE. In this case, permeability enhancement is given by both elastic and plastic strains as shear slip accumulates. Plastic strain further enhances fracture permeability, leading to smaller pressure build-ups and thus, to a better approximation of field data. Permeability enhancement is one order of magnitude larger for the viscoplastic model than for the elastic model. Obviously, permeability decreases during shut-in periods (associated to closure of the elastic portion of strain), but a significant fraction of the permeability enhancement is permanent, thus contributing to improved borehole injectivity. This behavior has been observed, e.g., in Basel, by comparing data acquired during the stimulation carried out in 2006 with that of hydrotests carried out years later (Häring et al., 2008; Ladner and Häring, 2009). Note that the timestamps of located microseismic events (Figure 5.3b) correspond approximately to the times of maximum permeability enhancement. This observation will be further discussed later.

The main limitation of the EP model, beyond the arbitrariness in manually modifying permeability, is that fracture permeability is homogeneous at any given time (Figure 5.4b). Using an embedded model (in which permeability is a function of volumetric strain) shows that permeability increases locally near the injection borehole and that the enhancement is lower away from the well. The longitudinal profile of fracture permeability displays an increase (around 3 orders of magnitude at maximum, Figure 5.4b) in fracture permeability due to the increase in fracture aperture (Figure 5.4c). Note that permeability enhancement occurs within the pressurized region of the fracture (Figure 5.4a). However, the permeability enhancement is moderate, with permeability remaining below 10^{-14} m² in EP and EE models, and thus, the predicted pressure build-up becomes excessively high compared to field measurements at late times (Figure 5.3). Considering shear failure and dilatancy yields an additional increase in fracture permeability of one order of magnitude that permits reproducing the measured pore pressure evolution at the injection borehole.



Figure 5.4 Profiles along the stimulated fracture of a) pressure build-up, b) fracture permeability, c) fracture aperture change ($b_0 = 2.25 \cdot 10^{-6} m$), and d) volumetric strain (and volumetric plastic strain (ε_{vp}) at t=1.75 h for model VE). Results are displayed at two moments for all models. The injection interval is located at d=0 and is positive upwards. Note the intersection with well ST2 around d=-12 m (Figure 5.2c).

The pore pressure build-up along the stimulated fracture (Figure 5.4a) mainly occurs within the reactivated region with irreversible strain (highlighted in green; Figure 5.4d). Figure 5.4a displays the fact that even though the EP model can reproduce measured pressures as good as the VE model at the injection borehole, pressure profiles along the fracture are significantly different. The EP model underestimates the pressure buildup within the reactivated region and overestimates it away the reactivated region. Until 1.75 h of injection, fracture aperture has already dilated and opened around 10 µm in the reactivated fracture patch (VE model, solid red line in Figure 5.4c). Model VE gives insights of the actual pore pressure distribution within the fracture.

5.3.2 Fracture reactivation

The contour plots of pore pressure at several stages of the stimulation (Figure 5.5) reveal that adjacent fractures and wellbores start to be pressurized after 2.6 h of stimulation. The pressurization becomes significant outside the stimulated fracture during the last phase of stimulation (t=3 h in Figure 5.5), when shearing has become relevant. This overpressure includes the low-permeability rock matrix and becomes marked after shearing, which indicates that it is largely driven by poroelastic effects (analytical solutions are available to gain insight into these effects (De Simone and Carrera, 2017)). These effects overlap with hydraulic connectivity (pressure diffusion) along fractures, apparent from the reduced pressure gradient along fractures in Figure 5.5. Hydraulic connection causes a non-negligible leak-off, which may be responsible for water back-flow into the injection wellbore outside the isolated interval. Bypass (back-flow to the section above the upper packer) was measured in the field during most stimulation experiments in BULGG. Leak-off can also be detected in the diagnostic plots of such stimulations by observing the derivative of injection pressure with respect to log-time as a function of time, which correlates well with the flow dimension n (Bourdet et al., 1983; Ramos et al., 2017). The flow dimensions are, in most cases, initially linear to bilinear (n=1 to 1.5), followed by an infinite acting radial flow period $(n\sim 2)$ during which flow occurs mainly along the fracture, and finally by a spherical flow period (n=2 to 3), which reveals the pressurization of the surrounding area and flow the overall medium via nearby fractures and boreholes.

Realism of the VE model is further supported by the anti-symmetric changes in pressure at the edges of the shearing region. Extension occurs away from the shearing tip at the side displacing towards the injection point (left side of the fractur at the top and right at the bottom in Figure 5.5a). (Vilarrasa et al., 2022, 2021) argue that this effect is one of the causes of delayed seismicity (aftershocks occurring some time after the main event). These extension zones would tend to fail, but become temporarily stabilized by the pressure drop. This mechanism may contribute to enhanced stimulation beyond the initial fracture and to broad block connectivity. Pressure increases on the other side of the fracture near the tip, thus yielding an antisymmetric poroelastic effect.



Figure 5.5 a) Contour plots of pore pressure at four stages of the stimulation (indicated with green stars in b) with the corresponding cumulative injected fluid volume V_{cum} using the VE model. b) Observed and simulated pressure evolution and injection flow rate at the injection borehole.

Further insight into the microseismicity mechanisms can be gained from the evolution of the deviatoric plastic strain during injection (shown for five fracture points in Figure 5.6c). The strain sharply rises after failure, coinciding with jacking of the fracture at that location, in all points (Figure 5.6a). Once jacking occurs, irreversible strain accumulates at a very low rate. The reactivation front, which coincides with the sharp increase in plastic strain, progressively advances away from the injection borehole. Plastic strain propagates by the end of the simulation (t=3.4h) along 45 m of the fracture, i.e., some 20 m away to each side of the injection borehole. Fracture reactivation propagates further upwards than downwards (Figure 5.6b). Even though it is common that seismic clouds develop predominantly upwards (Xie and Min, 2016), in this case, downwards propagation is limited by the presence of borehole ST2, which causes a local reduction in pore pressure because of its high permeability and inhibits further reactivation.



Figure 5.6 a) Temporal evolution of the deviatoric plastic strain at five points in the fracture (indicated in panel c); b) Profiles of deviatoric and volumetric plastic strains (ϵ_{dp} and ϵ_{vp} respectively) along the fracture at four times of the simulation (color coded with respect to time), the location of the monitoring points are indicated on the x axis; c) Contour plot of deviatoric plastic strain in the stimulated fracture at t=3.4 h. The five observation points are indicated on the x axis in panel b.

The stress paths of points 1-3 (location shown in Figure 5.6c) in the q-p ´ plane, i.e., deviatoric versus mean effective stress, display trajectories that move towards the failure surface until failure conditions are reached and then, the stress paths move along the failure surface (Figure 5.7). Note that the initial stress state is stable in all cases because the drainage of the tunnel increases the effective mean stress. Close to the injection borehole (point 1), the effective mean stress is reduced as liquid pressure increases with a progressive deviatoric stress increase. Further away (points 2 and 3), the deviatoric stress increases more pronouncedly at the beginning of injection because of stress transfer caused by slip of the portion of the fracture located closer to the injection borehole and because

the further away a point is located from the injection borehole, the longer it takes to the pressure front to reach that point. Failure occurs under compression in all cases (p > 0). A detailed look on the stress path at point 1 reveals a relation between timestamps of the stress path direction and those of measured induced microseismic events (Figure 5.3b). After the activation, the first time when stress path goes downward left, $t_{1-1}=1.64$ h, corresponds approximately to the timestamp of the first recorded microseismic event (t=1.704 h). Note that not all recorded microseismic events are plotted in Figure 5.3, but only the ones that could be located, i.e., some smaller magnitude events, below the magnitude of completeness of the seismic monitoring work, may have occurred before. Going downward-left lasts until $t_{1-2}=1.89h$, which approximately corresponds to the arrest of microseismicity (t=1.875 h). The second one starts at $t_{2-1}=2.63$ h and lasts until t_2 . $_2$ =3.04 h. The second onset of microseismicity (t=2.625 h) happens when stress path is near the Mohr-Coulomb failure line. The last located event (t=3.093 h) occurs slightly after t_{2-2} , during the shut-in phase. Similar qualitative conclusions are attained by observing the stress path of point 2, located 4.2 m away from the injection interval. In a nutshell, microseismicity develops since the stress path approaches the failure surface until it starts to go away from it. In the field, located seismic events aligned well with the simulated fracture fingerprint and developed (subject to the accuracy of the monitoring network) some 10 m downwards and 40 m upwards. The detailed spatio-temporal correlation between stress paths and timestamps of the located microseismic events is out of the scope of this work.



Figure 5.7 Effective stress path in the q-p' plane for the viscoplastic model (VE) and Mohr-Coulomb failure surfaces for points 1 to 3 located along the fracture (see Figure 5.6 for their location). The initial yield point indicates the onset of plastic deformation. A zoomed view for stress trajectories at point 1 is

provided with time stamps for the change of the stress path. Note that the depicted timestamps correspond to those of begin and arrest of induced microseismicity, as monitored in the field (see Figure 5.3b).

5.3.3 Response at nearby fractures

Pressurization of the stimulated fracture causes a poromechanical response of the rock matrix (Figure 5.8a) inducing changes in shear stresses that affect nearby fractures (Figure 5.8c). Initially, under low injection pressures, the induced shear stresses are reversible and would even vanish shortly after an eventual shut-in. However, once the stimulated fracture is reactivated, an irreversible shear stress drop (Goertz-Allmann et al., 2011; Kim et al., 2022; Yoo et al., 2021) occurs within the slipped fracture patch and the bulbs of positive shear stress are displaced towards its tips. As slip accumulates, the region with shear stress changes extends (see points I and J, at 20 m and 1 m from the stimulated fracture), affecting nearby fractures. Thus, the stimulation of a single fracture may modify also the stability of nearby fractures (De Simone et al., 2013).

Figure 5.8c displays the stress path at eight points located in four nearby fractures. For comparison purposes, all the axes have the same range of values. The failure surface is not plotted because it is placed far away to the left of the displayed paths, i.e., all points are stable during the whole stimulation. Some areas are barely affected by stimulation (points A and B, located far away from the stimulated fracture). In contrast, others experience significant stress changes (up to 3 MPa both in deviatoric and effective mean stress), e.g., points D to F, in the fractures right above and below the stimulated one. Some points approach shear failure conditions, either because of an increase in the deviatoric stress (point A), a decrease in the effective mean stress (point G), or a combination of both (point D). The trajectories are diverse, which highlights the complexity of pore pressure variations and stress changes that occur not only within the stimulated fracture, but also in its surroundings.





Figure 5.8 Stress paths (a) at four points in the rock matrix (I to L, depicted in panel b by squares), and (c) at eight points in nearby fractures (A to H, circles), respectively; the failure surface is located far away on the left side (all points are stable); b) Location of the selected points, with the shear stress (τ_{xy}) after 3.4 h in the background.

Shear failure conditions are also approached by a decrease in the effective mean stress and a slight decrease in the deviatoric stress (point E after 1.5 h of stimulation), which is usually the case when elastic poromechanical stress changes occur as a result of pore pressure increase (Vilarrasa et al., 2019). Yet, the trajectory at point E is more complex, showing an initial increase in deviatoric stress at constant effective mean stress, followed by a decrease in the deviatoric stress and effective mean stress, which could have been caused by shear-slip stress transfer and subsequent slip-driven pore pressure changes (Vilarrasa et al., 2021). Other sharp changes in the deviatoric stress are also induced by reactivation of the stimulated fracture (see points D and F). Other areas, affected by the stress shadow, move away from the failure surface by either increasing mean effective stress under constant deviatoric stress (point H) or by decreasing deviatoric stress under constant mean effective stress (point C).

5.3.4 Including more injection cycles in the viscoplastic model (VE)

The parameters of the model VE (Table 5.1) have been manually adjusted to render a good reproduction of the early stages of the stimulation (up to t=3.4 h, Figure 5.3a). We validate the model by adding more injection cycles. The numerical model reproduces pore pressure evolution at the injection borehole fairly well during the validation period (from t=3.4 h to t=8 h; Figure 5.9). Thus, we conclude that the VE model reproduces the progressive hydraulic stimulation of the fracture, which enhances permeability away from the injection well as the number of injection cycles accumulates (Figure 5.10).



Figure 5.9 Temporal evolution of pressure and flow rate at the injection borehole for a large number of injection cycles for model VE compared to the field measurements. The timestamps of located microseismic events are indicated with orange dots.

Field measurements display a sharper pressure response at the borehole, both at the onset of injection and after shut-in, which may indicate that jacking of the fracture only occurs after exceeding a certain pressure threshold, which is not fully captured by the numerical model (Figure 5.9). It must be acknowledged, however, that compliance effects (response of packers and monitoring devices to the high and fast changes in pressure) also affect data, so we are not overly concerned by sharp responses. The relevant issue is that a number of microseismic events could be located during the field experiment. They coincide with the injection periods as the fracture undergoes shear slip. However, some occur after shut-in (Figure 5.9), as is often the case in practice (Baisch and Vörös, 2010; X. Wang et al., 2023). Microseismic events occur in every injection cycle, when permeability surpasses the previously achieved maximum value (see the permeability evolutions for 8 points located within the stimulated fracture in Figure 5.10a), a few examples are indicated with dotted arrows in Figure 5.10a and a zoom is provided in Figure 5.10b, meaning that the previously reactivated fault patch is reached and the new reactivation is accompanied by microseismic events. This observation is related to the

Kaiser effect; materials retain a "memory" of previously applied stresses (Lavrov, 2003). In the course of successive hydraulic stimulations, induced seismicity is found to be triggered solely upon surpassing the previous maximum of Coulomb stress changes (Kim and Avouac, 2023) corroborating our findings. The nucleation process is delayed if the stress decreases and it resumes only upon the return of stress to its previous peak level. In our simulation, permeability enhancement is observed 50 m away from the injection well after t 8 h of injection, coinciding with a final swarm of microseismic events (Figure 5.10a). The timestamps of microseismic events in Figure 5.10a correspond well with the times of maximum mobilized friction angle (Figure 5.10c). The continuation of the stress path at point 1 (Figure 5.7) including more injection cycles in Figure 5.11 displays a repetitive recurrence where the periodicity of the fracture reactivation shows the microseismic threshold is concomitant to plasticity.



Figure 5.10 a) Temporal evolution of permeability at eight points (indicated in (d)) along the fracture together with timestamps of the microseismic events. The sharp permeability increase indicates when the pressure perturbation front reaches each point. b) Zoomed view of permeability evolution at point 1 to highlight the relation between permeability enhancement and microseismic threshold. c) Mobilized friction angle (Eq. (10)) during injection at point 1. d) Location of the 8 control points along the fracture, with the permeability contour plot after 8 hours of stimulation in the background. As a reference, point P8 is located 50 m away from the injection well.



Figure 5.11 Stress path at point 1 as in Figure 5.7 for the larger number of injection cycles with a zoom in the critical area. The failure surfaces at peak and residual friction are based on Mohr-Coulomb failure criterion.

5.4 Discussion

The comparison between pore pressure evolution calculated by three models highlights that a viscoplastic model with strength weakening and dilatancy and computing fracture permeability changes as a function of volumetric strain assuming the cubic law (model VE) is needed, to reproduce field observations of hydraulic stimulation of crystalline rock. The elastic (EP and EE) models forecast significantly larger overpressures compared to the measured ones at the timestamps of microseismic events (orange dots in Figure 5.3). Thus, according to elastic models, microseismic events after shear failure should have occurred way before. This discrepancy suggests that the fracture was undergoing progressive shear slip and opening due to dilatancy, and thus permeability enhancement when the microseismic events were monitored. Furthermore, the validity of the implemented conceptual model including viscoplasticity is also confirmed by model validation, i.e., simulating further injection cycles not used for calibrating the model (Figure 5.9).

The comparison between permeability profiles along the fracture indicates a greater enhancement of permeability (Figure 5.4b) due to the larger dilatancy-induced increase of fracture opening in the viscoplastic model. The permeability enhancement of up to three orders of magnitude extends up to 40 m along the fracture towards the end of the calibration period ($t\sim3.4$ h). Figure 5.4a highlights the differences in pore pressure along the fracture for the three models once the fracture is reactivated (t>0.65 h). Simulation results show that when the permeability is manually and homogeneously adjusted in the whole fracture (model EP), pore pressure diffuses along the whole fracture, yielding a pore pressure distribution that significantly differs from the actual one. When simulating variable permeability as a function of the injection-induced fracture aperture changes (Embedded models; EE and VE), pore pressure diffusion occurs slowly away from the stimulated fracture patch because of the low initial fracture permeability. Fracture opens up where pore pressure increases, and an additional dilation occurs in model VE when shear failure conditions are reached, yielding a progressively fracture stimulation in which permeability is enhanced (Peach and Spiers, 1996; Simpson et al., 2001; Ye and Ghassemi, 2018). The effect of the additional permeability enhancement caused by shear slip is evident when comparing the pore pressure profiles of models EE and VE, i.e., pressure build-up is lower in the viscoplastic model than in the elastic one.

Reducing the effective normal stress causes shear displacement, dilation and permeability enhancement of the natural fracture. Almost 90% of the slip displacement and dilation is estimated to occur after fracture shear failure (Xiao et al., 2019). After fracture activation, stress trajectories in the stimulated fracture follow a similar pattern in each injection cycle, i.e. decreasing both effective normal and deviatoric stress during injection and increasing again to a similar state developing fracture reactivation (Figure 5.7). This pattern would be observed in points far away the injection borehole after enough time for the reactivation front to reach distant points. These reactivation cycles are matched with the timestamps of seismic events.

When stimulating a fracture, the perturbation is not restricted to the fracture itself because (1) pore pressure diffuses, mainly through fractures, (2) induced poromechanical strain-stress changes extend further away than the stimulated fracture, and (3) shear stress transfer modifies the state of stress around the slipped patch of the fracture (Figure 5.8c), which may either promote shear failure of nearby fractures or inhibit it (stress shadow) (Safari and Ghassemi, 2016). When shear slip occurs along a fracture, the stress drop is right-lateral (blue colors in Figure 5.8c). The induced right-lateral shear stress is not restricted to the slipped patch and forms two lobes at the tips of the slipped area that affect portions of nearby fractures, creating the so-called stress shadow (Taghichian et al., 2014), which inhibits shear slip of these regions. The phenomenon of stress shadow refers to the development of a localized area exhibiting high compressive stresses that are oriented perpendicular to the fracture face in the vicinity of the fracture center. This results in the reorientation of the direction of maximum stress within the region of the stress shadow (Waters et al., 2009). Thus, if subsequent hydraulic stimulations are performed in nearby fractures, the portions affected by the stress shadow may not be reactivated and permeability enhancement would be limited. On the contrary, the areas affected by the yellow-reddish colors in Figure 5.8c experience left-lateral shear stress that favors subsequent fracture reactivation if these fractures are stimulated. Note that the fractures placed close to the stimulated fracture contain both areas where shear slip is either promoted or inhibited.

The primary mechanism behind the manifestation of microseismic events is explicable by means of hydroshearing of pre-existing natural fractures that reach failure conditions (Yoon et al., 2017). Induced microseismicity is a phenomenon naturally accompanying plastic, i.e, irreversible, deformations. The involved hydromechanical processes including pressure increase, fracture dilation, permeability enhancement, and consequent microseismicity are well captured by our fully coupled viscoplastic model. The similar timestamps of plastic dilation (and pertinent permeability enhancement) and microseismic events (Figure 5.10) further support the model. (Minakov and Yarushina, 2021) have developed a poro-elastoplastic model to clarify the connection between the components of the seismic moment tensor and the failure process through the analysis of the acoustic emission during rock deformation. The model connects the localized failure pattern, plastic dilation ($\sin \psi$), and corresponding seismic response. Plasticity can explain induced microseismic source mechanisms. Further studies should focus on finding correlations between the spatiotemporal development of microseismicity (subject to the accuracy of the monitoring network) and the extent of the zone suffering from viscoplastic instability.

In induced seismicity, a hysteresis phenomenon known as the Kaiser effect (Lavrov, 2003), is frequently observed (Baisch et al., 2010; Dempsey and Riffault, 2019). This effect is characterized by the gradual failure of a material subjected to a series of increasing amplitude loading cycles, wherein subsequent failures typically occur at stress levels exceeding those reached in prior cycles. This effect elucidates the observation that acoustic emissions during rock failure cease when stress levels decrease and only resume once the medium is reloaded to its previous maximum (Minakov and Yarushina, 2021). It is anticipated that the Kaiser effect exhibits significant impact within a singular injection stage but displays lesser relevance between successive stages (Multi-stage injection).

Modeling hydraulic stimulation presents challenges due to the involvement of complex physical processes, such as rock deformation, fluid flow, and fracture initiation and propagation (Chen et al., 2022; Wu et al., 2022). The complexity of hydraulic stimulation arises from several factors, such as the coupling of fluid flow inside fractures with rock and fracture deformation; the involvement of multiscale and multi-physics processes like the interaction between natural and hydraulic fractures, leak-off, and rock heterogeneity; and the difficulty in accurately modeling geological and operational conditions due to limited data availability and high costs. The challenge remains in scaling up numerical simulation capabilities from single fracture stimulation in a laboratory setting to multiple fractures at the field scale in industrial projects. This upscaling necessitates the development of more efficient numerical methods that can effectively manage the increased demand for computational resources. In order to make the study of hydraulic stimulation more tractable, some aspects of the problem need to be simplified or ignored in numerical simulations, leading to the development of multiple modeling approaches with varying applicability and limitations. We show that a viscoplastic model that accounts for strength weakening, dilatancy, and fracture permeability evolution as a function of volumetric strain enables numerical models to accurately reproduce hydraulic stimulation in crystalline rocks, thereby enhancing the understanding of the underlying processes and improving the capability to forecast hydraulic stimulation outcomes.

5.5 Conclusion

We have modeled one of the hydraulic stimulations performed at the BULGG using three different approaches. Despite reproducing a well-fitted pressure evolution curve, the model with manually calibrated permeability lacks the ability to capture the pore pressure distribution along the fracture, and consequently the poromechanical response at the rock matrix and nearby fractures, because permeability is assumed homogeneous along the fracture. Considering the embedded model to simulate permeability enhancement following the cubic law as a function of the volumetric strain improves the estimation of the spatio-temporal distribution of pressure. Yet, pressure is overestimated after the onset of fracture slips when assuming elastic behavior. To satisfactorily reproduce field measurements, an additional permeability enhancement is required in the post-failure stage, which is achieved with a viscoplastic model with strain weakening and dilatancy. This viscoplastic model, whose parameters have been manually adjusted to render a good fit of the early stages of stimulation, has been validated by extending the simulation to further injection cycles. Microseismic events in each cycle occur once plastic strain and, thus, permeability surpass the maximum value achieved in previous injection cycles. Furthermore, post-injection microseismicity becomes more perceptible as injection cycles accumulate. The timestamps of monitored microseismic events are well predicted by the viscoplastic model, which predicts unstable conditions at the time of the seismic clouds showing that the induced microseismic threshold is concomitant to plasticity. The correlation between plasticity and induced microseismic events is illustrated by stress trajectories, which show that the timestamps of monitored microseismicity at the field laboratory coincide with the periods at which the fracture undergoes shear failure conditions. Furthermore, the viscoplastic model reproduces the coupled processes in a natural way, thus avoiding the tedious, subjective and prone-to-error manual calibration of the spatio-temporal evolution of permeability.

In summary, the proposed VE model accounts for fracture reactivation and dilatancy and allows good reproduction of observed pressure evolution, three orders of magnitude irreversible increases in permeability and the timing of microseismic events. We conclude that the insights yielded by this model are supported by observations. We conjecture that they can be extended beyond the processes and extent of the hydraulic stimulation, into a comprehensive understanding of the hydromechanical response of the subsurface to fluid injection and associated (micro) seismicity.

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CONCLUDING REMARKS

This thesis advances the understanding of the hydro-mechanical response of fractured rocks to fluid injection, with direct implications for geo-engineering and geo-energy applications, such as hydraulic stimulation of low-permeability fractured rock, geologic carbon storage, and hydraulic fracturing operations. A comprehensive exploration of coupled HM processes influencing seismicity during the stimulation and injection operations of EGS has been undertaken. The main conclusions of the Thesis are summarized below.

The investigation of the hydraulic response to water injection into a fracture surrounded by low-permeability rock has unveiled important insights. Notably, the analysis of pressure evolution has highlighted the non-negligible impact on fluid flow of leakage despite the low-permeability rock matrix. It is revealed that fractures exhibit a leaky nature, challenging the conventional assumption of impermeable matrix in certain modeling approaches (it is usually done when dealing with low-permeability media in approaches like DFN, DEM, and SFM). The short transition time to leakage-dominated flow, coupled with the potential for a prolonged leakage-dominated regime, underscores the significance of accounting for leakage in interpreting injection tests and modeling fractured media. Neglecting leakage has been shown to result in an overestimation of fracture transmissivity by a factor of two and the pressure perturbation front by a few orders of magnitude.

A novel approach involving the derivation of equivalent HM properties for an equivalent-continuum layer, significantly thicker than the represented fracture, has been proposed. The method has demonstrated the ability to achieve identical simulation results for equivalent fracture layers with centimeter-scale thickness as the actual fracture aperture at the micrometer scale. This upscaling approach enhances the tractability of fracture discretization while preserving accuracy, presenting a useful method for modeling geo-energy and geo-engineering applications in fractured media across varying scales.

Furthermore, the modeling of hydraulic stimulations at the BULGG using different approaches has yielded valuable insights. The limitations of a manually calibrated permeability model have been identified, emphasizing the need for a more nuanced representation of permeability enhancement. An elastic poromechanical fracture representation accounting for permeability changes proportional to the cube of fracture aperture, i.e., cubic law, is capable of reproducing the observed pressure evolution in the field until the fracture is reactivated. Subsequently, a viscoplastic model, incorporating strain weakening and dilatancy, has proven instrumental in reproducing observed pressure evolution, irreversible increases in permeability, and the timing of microseismic events. The model ability to predict stress trajectories and illustrate the correlation between plasticity and induced microseismic events offers a natural and comprehensive understanding of coupled processes, mitigating the need for subjective and error-prone manual calibration. The proposed viscoplastic model, with its capacity to account for fracture reactivation and dilatancy, aligns well with observed phenomena and provides a robust foundation for extending insights beyond hydraulic stimulation processes. The findings not only contribute to the understanding of (micro)seismicity in EGS, but also offer broader implications for comprehending the HM response of the subsurface to fluid injection across various applications. This thesis, through its multifaceted exploration, marks a considerable contribution to the academic and professional discourse in the field.

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Publications and conference presentations

Articles in the process of publications

I. Vaezi, V. Vilarrasa, F. Parisio, and K. Yoshioka. On the leaky nature of fractures in low-permeability rock. submitted.

I. Vaezi, A. Alcolea, P. Meier, F. Parisio, J. Carrera, and V. Vilarrasa. Numerical modeling of hydraulic stimulation of fractured crystalline rock at the Bedretto Underground Laboratory for Geosciences and Geoenergies. submitted.

I. Vaezi, F. Parisio, K. Yoshioka, A. Alcolea, P. Meier, J. Carrera, S. Olivella, and V. Vilarrasa. *Implicit hydro-mechanical representation of fractures using continuum approach.* submitted.

S. K. Tangirala, F. Parisio, I. Vaezi, and V. Vilarrasa. *Effectiveness of injection* protocols for hydraulic stimulation in Enhanced Geothermal Systems. submitted

I. Vaezi, K. Yoshioka, S. De Simone, B. Gómez, A. Paluszny, M. R. Jalali, I. Berre, S. Olivella, J. Rutqvist, K. Min, Q. Lei, R. Y. Makhnenko, C. Tsang, and V. Vilarrasa, A review on thermo-hydro-mechanical modeling of coupled processes in fractured rocks: A continuum to discontinuum perspective. Under revision by co-authors.

Presentations in conferences

I. Vaezi, A. Alcolea, P. Meier, F. Parisio, J. Carrera, and V. Vilarrasa, May 2023, Numerical simulation of hydroshearing in fractured crystalline rock at the Bedretto Underground Laboratory (Switzerland), InterPore2023, Edinburgh, Scotland.

I. Vaezi, V. Vilarrasa, F. Parisio, and K. Yoshioka, Nov. 2022, *Implicit* representation of a single fracture with a continuum equivalent layer to simulate coupled processes, 3rd International Conference on Coupled Processes in Fractured Geological Media (CouFrac2022), California, USA.

I. Vaezi, V. Vilarrasa, F. Parisio, and K. Yoshioka, Apr. 2021, Numerical simulation of coupled processes in a single fracture employing a continuum approach, European Geosciences Union General Assembly 2021 (EGU21), Vienna, Austria.

I. Vaezi, V. Vilarrasa, F. Parisio, and K. Yoshioka, Nov. 2020, *Modeling coupled processes in fractured media using a continuum approach*, 2nd International Conference on Coupled Processes in Fractured Geological Media (CouFrac2020) Seoul, S. Korea.
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