Characterisation and modelling of natural fracture networks: geometry, geomechanics and fluid flow

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Thesis Summary for the ISRM Rocha Medal Award
Attribution

The PhD thesis has resulted in eight journal articles and four conference papers, which are listed as below corresponding to different chapters of the thesis.

Chapter 2


Chapter 3


Chapter 4


Chapter 5


Chapter 6


Chapter 7


Chapter 8


Chapter 9

Key points

Problem statement

Natural fractures often dominate the bulk behaviour of crustal rocks. Thus, the characterisation and modelling of the non-trivial effects of fractures on the hydromechanical properties (e.g. strength, deformability, permeability and anisotropy) of fractured rocks is an important rock mechanics problem and is relevant to many rock engineering applications such as civil construction, hydrocarbon extraction, geothermal production, and geological disposal. In Chapter 1 of the thesis, three key rock engineering problems are identified and eight important scientific and engineering questions are specified, according to which the structure of the thesis is designed.

Appreciation of state-of-the-art

A thorough review is presented in Chapter 3 on the state-of-the-art of using discrete fracture networks (DFNs) for modelling geometrical characteristics, geomechanical evolution and hydromechanical behaviour of fractured rocks. The DFN models reviewed include those based on geological mapping, stochastic generation and geomechanical simulation. Different types of continuum, discontinuum and hybrid geomechanical models that integrate DFN information are reviewed. Numerical studies aiming at investigating geomechanical effects on fluid flow in DFNs are further reviewed.

Theoretical and practical advancements

Theoretical advancements: A tectonic interpretation is presented to explain the connectivity evolution of a multiscale natural fracture system, which provides an answer to the open question about whether natural fractures are well or poorly connected (Chapter 2). A novel computational framework has been developed for incorporating detailed geological information and modelling complex fracture behaviour in numerical simulations (Chapter 4). By using this model, the validity of the commonly-used Poisson DFN method in representing real fracture systems has been examined (Chapter 5) and the stress-dependent permeability of fracture networks has been explored (Chapter 5, 7 & 8). A novel scheme accommodating discrete-time random walks in a recursive self-referencing lattice has been developed to generate realistic fracture patterns at larger scales with the important geostatistical and geomechanical characteristics preserved (Chapter 6).

Practical advancements: A practical workflow for modelling the geometry, geomechanics and fluid flow in fractured rocks has been developed and applied to simulate the hydromechanical behaviour of realistic fracture systems in rock (Chapters 5, 7 & 8). A new workflow for upscaling small-scale, high-resolution simulation results for estimating larger scale properties has been developed (Chapter 6). A practical workflow for incorporating field fracture data into the excavation damaged zone modelling has also been presented (Chapter 9). These workflows provide rock engineers with very useful tools for practical design and analysis.

Verification of proposed solution

The numerical model developed for simulating rough fracture behaviour has been verified against the well-established empirical solutions [Barton and Choubey, 1977; Barton et al., 1985] with respect to normal closure, shear strength, and dilational displacement (Chapter 4). The fracture network upscaling approach has been validated both qualitatively and quantitatively against the field data of the real fracture network map (Chapter 6). The research findings of stress-dependent fluid flow (Chapters 5, 7, 8) show consistency with field observations in the literature, e.g. commonly only a small portion of fractures are conductive [Tsang and Neremnies, 1998; Follin et al., 2014], permeability is less sensitive in deep rocks [Rutqvist and Stephansson, 2003], and critically stressed faults tend to have much higher hydraulic conductivity [Barton et al., 1995; Zoback, 2007]. The excavation damaged zone research (Chapter 9) confirms the important effects of pre-existing fractures on damage evolution around underground excavations as reported in the literature [Tsang et al., 2005].
Abstract

Natural fractures are ubiquitous in crustal rocks and often dominate the bulk properties of geological media. The understanding of the geometrical, geomechanical and geohydrological behaviour of natural fracture networks is a challenging issue which is relevant to many rock engineering applications. This thesis first presents a study of the statistics and tectonism of a multiscale fracture system in limestone with a conceptual interpretation proposed to the underlying mechanism of complex fracture network formations. A critical review is then presented on the state-of-the-art discrete fracture network modelling of coupled hydromechanical processes in fractured rocks. In this research, to model the geomechanical behaviour of natural fractures in rock, a joint constitutive model (JCM) is implemented into the numerical framework of the finite-discrete element method (FEMDEM). The combined formulation can compute the stress/strain evolution in intact rocks, capture the mechanical interaction between matrix blocks, characterise the non-linear deformation of rough fractures and mimic the propagation of new cracks. This geomechanical model is applied to calculate the aperture distribution of various metre-scale fracture networks under in-situ stress conditions, based on which stress-dependent fluid flows are analysed. A novel upscaling approach employing discrete-time random walks is developed to extrapolate fracture network geometries together with their variable apertures into larger scales for permeability prediction. The JCM-FEMDEM model is further used to simulate the damage evolution around an underground excavation in a crystalline rock embedded with pre-existing discontinuities. The scope of this thesis covers the scenarios of both two-dimensional (2D) and three-dimensional (3D) natural fracture networks that also accommodate stress-induced new cracks. The research findings demonstrate the importance of realistic fracture network representation and systematic geomechanical simulation for modelling the hydromechanical behaviour of fractured rocks.

Keywords: Fractured rock; Geomechanical model; FEMDEM; Stress; Permeability; Scaling
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1. Introduction

Fractures such as faults, joints and veins are ubiquitous in crustal rocks. These naturally occurring discontinuities often form complex networks and create highly disordered geological conditions. The widespread presence of natural fractures raises a fundamental question about the underlying mechanisms that drive such complicated evolutionary and collective phenomena. Fractures that nucleate from initial flaws [Pollard and Aydin, 1988] may propagate in different strain rate regimes, i.e. the subcritical, quasi-static and dynamic regimes [Schultz, 2000]. Continued strain under an increased remote displacement loading or a sequence of tectonic episodes can promote the interactions of multiple fractures (e.g. coalescence, cross-cutting, inhibition, reorientation and arrest) [Price and Cosgrove, 1990]. Such mechanically-controlled processes result in complex fracture networks with self-organised (i.e. non-random) population statistics, e.g. density, lengths, locations, spacing, intersections, orientations and displacements [Olson, 1993; Renshaw and Pollard, 1994; Bonnet et al., 2001], which have important consequences on rock engineering applications.

Fractures, along which rupture has caused cohesion loss and mechanical weakness in the rock, often dominate the strength and deformation of geological formations [Hoek, 1983]. Interconnected fractures can serve as conduits or barriers for fluid and chemical migration in subsurface [Berkowitz, 2002]. The characterisation and simulation of the effects of natural fractures on the hydromechanical behaviour of geological media is a challenging issue [Zimmerman and Main, 2004], which is relevant to a variety of engineering applications such as hydrocarbon extraction, geothermal production, groundwater remediation and geological disposal of radioactive waste [Rutqvist and Stephansson, 2003]. Several key issues in hydromechanical modelling of fractured rocks are summarised as follows:

- Characterisation and representation of the geometry of natural fracture systems [Bonnet et al., 2001], and understanding of the underlying mechanisms that create the observed complexities [Pollard and Aydin, 1988].
- Development of computational methods for simulating discontinuous phenomena in fractured rocks, including interaction of discrete matrix bodies [Jing, 2003], fracturing and fragmentation of intact rocks [Hoek and Martin, 2014], opening, shearing and dilation of rough fractures [Barton, 2013], fluid flow through fractured porous space [Berkowitz, 2002], and coupled hydromechanical processes [Tsang, 1991].
- Upscaling of small-scale simulation results for large-scale predictions with the consideration of the scaling nature of natural fracture systems, which may not have any representative elementary volume (REV) [Bonnet et al., 2001].

The thesis aims to advance the understanding of the geometrical complexity of natural fracture networks (Chapter 2), review the state-of-the-art discrete fracture network modelling (Chapter 3), develop a computational framework for geomechanical modelling of rough rock fractures (Chapter 4), investigate the stress effects on fluid flow in 2D (Chapter 5) and 3D (Chapters 7 & 8) fracture networks, predict larger-scale fracture network properties through upscaling smaller-scale simulation results (Chapter 6), and further apply the numerical tools to solve engineering problems (Chapter 9). Finally, the implications for rock engineering applications are discussed and conclusions are drawn (Chapter 10).

2. Geometry and tectonism of natural fracture networks

The growth and interaction of natural fractures result in a hierarchical geometry that may exhibit long-range correlations from macroscale frameworks to microscale fabrics [Barton, 1995]. The proximity of the connectivity state of natural fracture networks to the percolation threshold remains an unresolved debate. It was argued earlier that natural fracture systems are close to the percolation threshold [Renshaw, 1997], because the driving force (tectonic stress or hydraulic pressure) is abruptly released once the system is connected, and a diminished mechanical strength and an enhanced hydraulic conductivity are likely to occur [Chelidze, 1982; Madden, 1983; Gueguen et al., 1991; Renshaw, 1996]. However, extensive field observations suggest that crustal fractures can be
well-connected and significantly above the threshold [Barton, 1995]. The geometrical scaling of a fracture population provides clues for a better understanding of the geology and physics behind the statistics. The power law model having no characteristic length scale can be a useful tool to interpret the scaling phenomena of natural fracture systems [Bonnet et al., 2001].

The fracture networks studied here are located in the Languedoc region of Southern France. A study of the regional geological evolution indicates that this area has been affected by multiple tectonic events: normal faulting in the Jurassic (Event I), strike-slip faulting (Event II-A) and thrusting faulting (Event II-B) in the Late Cretaceous to Eocene, and normal faulting in the Oligocene (Event III). A series of outcrop patterns exposed at the Earth’s surface over various scales is mapped to measure the statistics of the fracture system (Fig. 1).

**Fig. 1** A compilation of multiscale fracture patterns from the Languedoc region in Southern France. (a) A regional-scale lineament pattern generated from the regional structural map, (b)-(d) intermediate-scale fracture patterns obtained from aerial photographs and (e)-(g) local-scale outcrop patterns derived from geological exposures.

The spatial organisation is characterised by the fractal dimension \( D \) (≈ 1.65), which is derived using the two-point correlation function \( C_2(r) = N_d(r)/N \sim r^D \), where \( N \) is the total number of fracture barycentres and \( N_d \) is the number of pairs of barycentres whose distance is smaller than a scale variable \( r \) (Fig. 2a) [Bour and Davy, 1999]. The distribution of fracture lengths is characterised by the power law exponent \( a \) (≈ 2.65), which is derived from the density distribution \( n(l, L)dl = aL^Dl^a \), where \( l \) is the fracture length, \( L \) is the domain size, and \( a \) is a density term (Fig. 2b) [Bour et al., 2002]. Fractures having a broad-bandwidth power law size distribution are not randomly placed in the geological media, but organised by mechanical interactions that occur during their growth process [Darcel et al., 2003; Davy et al., 2010, 2013]. The relationship between \( a \) and \( D \) of the dataset studied, i.e. \( a \approx D+1 \), indicates that the multiscale fracture system may be self-similar [Bour et al., 2002]. A self-similar fracture pattern can emerge under a statistically-valid hierarchical rule that a large fracture inhibits smaller ones from crossing it but not the converse [Davy et al., 2010]. The average distance \( d(l) \) between the centroid of a
fracture having length $l$ and that of the nearest larger neighbour is theoretically correlated with $l$ as $d(l) \propto l^x$ [Bour and Davy, 1999], where $x = (a-1)/D$. The current data fit to $x = 1.0$ (Fig. 2c), suggesting that the distance of a fracture to its nearest larger one is linearly correlated with its size, and that the faults and joints were well developed and had reached quite a dense state controlled by mechanical interactions [Davy et al., 2010]. In addition, the fracture patterns on different scales also exhibit quite similar values in the ratio of $d(l)/l$, implying that the fracture interactions may be governed by a similar mechanism over different scales (this may seem surprising given that faulting is a different brittle process to jointing).

Fig. 2 (a) Calculation of the normalised two-point correlation functions $C_2(r/L)$ as a function of $r/L$. The dashed line represents a power law fitting line with the fractal dimension $D = 1.65$. (b) The normalised density distribution of fracture lengths of the multiscale fracture patterns; the dashed line represents a power law fitting line with an exponent $a = 2.65$ and a density term $\alpha = 3.0$. (c) Scaling of the distance $d(l)$ between the barycentre of a fracture and that of its nearest neighbour having a length larger than $l$; the dashed line represents a power law fitting line with an exponent $x = 1.0$.

The percolation parameter $p$ as a connectivity metric of fracture networks is calculated using the following equation [Berkowitz et al., 2000]:

$$ p(l, L) = \int_{l_{\text{min}}}^{L} \frac{n(l, L)l^\alpha}{L^D} dl + \int_{l}^{l_{\text{max}}} n(l, L) dl $$

where $l_{\text{max}}$ is the maximum fracture length, and $l_{\text{min}}$ is the length over which all fractures were correctly sampled (corresponding to the onset of power law length scaling in each network). The connectivity of a fracture network is made up of two parts, as shown in Eq. (1): the first part describes the contribution made by fractures smaller than the system size $L$ and the second represents the contribution from fractures larger than $L$ [Bour and Davy, 2010].
Mathematically, the connectivity of a self-similar fractal population is scale invariant [Darcel et al., 2003], and the networks are connected at all scales if $p$ is larger than the percolation threshold $p_c$ (i.e. the onset above which a fracture network is, on average, connected from one side of the domain to the other). The range of $p_c$ was determined to be between 5.6 and 6.0 based on 2D random fracture network realisations [Bour and Davy, 1997]. A correcting factor of $2/\pi$ was suggested to derive a $p_c$ for 3D systems [Lang et al., 2014], which yields $p_c \approx 3.6-3.8$. The $p$ value of the fracture patterns in the study area varies significantly at different scales, ranging from 4.60 to 14.69. The effects of the variation in $a$ and $D$ for different samples and the inconsistency in the ratio of $L/l_{\text{min}}$ may not sufficiently explain the high contrast in the calculated $p$ values.

An understanding of the process by which the natural fracture networks evolve might offer an explanation for this. Fracture networks in rock develop over geological time by the superposition of successive fracture sets each linked to a different stress regime and set of crustal conditions. Thus, there is a strong possibility that early fracture sets may become partially or totally cemented as the network evolves and fluids move through it. These sealed or partially sealed early fracture sets may act as barriers to fluid flow and the integrity of the rock has been to some extent recovered. Although the network geometrically remains almost the same, its “effective” connectivity has been reduced well below the percolation threshold. As a result, subsequent stress fields could continue to propagate new fractures until the critical state is re-established. However, if the “apparent” connectivity of trace patterns is measured without taking into account their internal sealing conditions, it is likely to derive a percolation state significantly above the threshold. In addition, the intrinsic anisotropy of the fracture network may also permit tectonic energy to accumulate in other directions which have a higher mechanical strength/stiffness and can accommodate more new cracks.

Table 1 Percolation parameters of the progressively formed fracture networks at the end of each different formation stage.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Stage 1 (Event I)</th>
<th>Stage 2 (Event II-A)</th>
<th>Stage 3 (Event II-B &amp; III)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP</td>
<td>3.87</td>
<td>5.05</td>
<td>7.18</td>
</tr>
<tr>
<td>IP1</td>
<td>3.06</td>
<td>4.30</td>
<td>5.30</td>
</tr>
<tr>
<td>IP2</td>
<td>8.16</td>
<td>12.62</td>
<td>14.69</td>
</tr>
<tr>
<td>IP3</td>
<td>3.62</td>
<td>5.69</td>
<td>6.90</td>
</tr>
<tr>
<td>LPs</td>
<td>--</td>
<td>4.38 ± 1.54</td>
<td>6.81 ± 2.17</td>
</tr>
</tbody>
</table>

To test this concept, the percolation parameter of the progressively developed fracture networks at the end of each different formation stage is calculated (Table 1), which is achieved simply by re-analysing networks from field data with the appropriate later-staged fractures removed based on the relation between fracture orientations and the tectonic events. Generally, the first stage fracture set exhibits a connectivity state close to the percolation threshold, consistent with the postulation of energy relief at the connecting moment observed in both laboratory experiments [Chelidze, 1982] and numerical simulations [Madden, 1983; Renshaw, 1996; Zhang and Sanderson, 1998]. However, because of the possibility of early fractures becoming cemented as has been observed in the Languedoc area [Petit and Mattauer, 1995; Petit et al., 1999], a fracture network which at the time of its formation was at the percolation threshold may subsequently have an “effective” connectivity considerably lower than $p_c$. Thus, in response to later tectonic events, further cracking may occur within the network until the system once again becomes connected. The incremental rate of $p$ caused by late-stage fracturing seems to gradually decrease due to the presence of early-stage fractures, since percolation can be reached more easily by reactivating and/or coalescing existing fractures rather than generating new ones. The exceptionally high $p$ in the pattern of IP2 may be attributed to its location very close to one of the regional-scale faults, in the vicinity of which concentrated fracturing paced by active calcite precipitation may occur, i.e. more intensive “crack-seal” cycles may be involved [Petit et al., 1999].
3. State-of-the-art discrete fracture network modelling

The recognition of the importance of natural fractures, which can result in heterogeneous stress fields [Pollard and Segall, 1987] and channelised fluid flow pathways [Tsang and Neretnieks, 1998] in highly disordered geological formations, has promoted the development of robust discrete fracture network (DFN) models for numerical simulation of fractured rocks [Herbert, 1996]. The purpose of this review is to present a summary of various approaches that explicitly mimic natural fracture geometries, and different numerical frameworks that integrate discrete fracture representations for modelling the geomechanical behaviour of fractured rocks as well as further analysis of the impacts on fluid flow.

The geometry of a fracture network model can be generated from geological mapping, stochastic realisation or geomechanical simulation. The geologically-mapped fracture patterns are derived from the exposure of rock outcrops or man-made excavations [Zhang and Sanderson, 1996; Belayneh and Cosgrove, 2004]. The stochastic DFN approach generates randomly distributed fracture networks in which the geometrical properties (e.g. position, size, orientation, aperture) of fractures are treated as independent random variables obeying certain probability functions [Baecher, 1983; Dershowitz and Einstein, 1988]. The geomechanically-based DFN method reproduces natural fracture patterns by applying a geologically-inferred palaeo-stress/strain condition and progressively solving the perturbation of stress fields and capturing the nucleation, propagation and coalescence of discrete fractures [Olson, 1993; Renshaw and Pollard, 1994; Palaszyn and Mathäi, 2009]. The three types of DFN models have distinct strengths but also suffer from some limitations, as summarised in Table 2.

The geomechanical modelling of fractured rocks can be achieved by continuum or discontinuum approaches, which have important differences in conceptualising geological media and treating displacement compatibility [Jing, 2003]. The continuum approach treats a rock domain as a continuous medium that can be solved by the finite element method [Oda et al., 1993] or finite difference method [Rutqvist et al., 2013]. The discontinuum approaches can explicitly model irregular fracture networks, include complex constitutive laws of rock materials and fractures, and capture the fracturing and fragmentation processes. The commonly used discontinuum models include the distinct element method [Cundall, 1971], the discontinuous deformation analysis method [Shi and Goodman, 1985], the bonded-particle method [Mas Ivars et al., 2011], and the combined finite-discrete element method (FEMDEM) [Munjiza, 2004]. The preference for a continuum or discontinuum modelling scheme depends on the scale of the problem and the complexity of the fracture system [Jing and Hudson, 2002]. A detailed comparison of the strengths and limitations of different types of continuum and discontinuum models can be found in Table 2.

The geomechanical effects on the hydrological properties of fractured rocks has also been investigated with respect to stress-dependent flow pattern, equivalent permeability and mass transport in the literature [Zhang and Sanderson, 1996; Min et al., 2004; Baghbanan and Jing, 2008; Latham et al., 2013; Rutqvist et al., 2013; Zhao et al., 2013]. Several important stress-dependent fluid flow phenomena have been observed such as permeability reduction caused by fracture closure, flow localisation engendered by shear dilation, permeability increase at the critical stress ratio condition, and breakthrough curve shifting with the in-situ stress variation. The stress-dependent fluid flow in fractured rocks demonstrate the importance of using explicit DFN representations and incorporating geomechanical modelling for characterising fluid flow in natural fracture systems. The previous simulation results also show consistency with field measurements or observations, such as commonly only a small portion of fractures are conductive [Tsang and Neretnieks, 1998], permeability is less sensitive in deeper formations [Rutqvist and Stephansson, 2003], and critically stressed faults tend to have much higher hydraulic conductivity [Zoback, 2007].
<table>
<thead>
<tr>
<th>Numerical models</th>
<th>Key inputs</th>
<th>Strengths</th>
<th>Limitations</th>
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<tbody>
<tr>
<td>Geometrical modelling</td>
<td></td>
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<tr>
<td>Geological DFNs</td>
<td>Analogue mapping, borehole imaging, aerial photographs, LIDAR scan or seismic survey</td>
<td>• Deterministic characterisation of a fracture system</td>
<td>• Limited feasibility for deep rocks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Preservation of geological realisms</td>
<td>• Difficulty in building 3D structures</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>• Constraints from measurement scale and resolution</td>
</tr>
<tr>
<td>Stochastic DFNs</td>
<td>Statistical data of fracture lengths, orientations, locations, shapes and their correlations</td>
<td>o Simplicity and convenience</td>
<td>o Uncertainties in statistical parameters</td>
</tr>
<tr>
<td></td>
<td></td>
<td>o Efficient generation</td>
<td>o Oversimplification of fracture geometries and topologies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>o Applicability for both 2D and 3D</td>
<td>o Requirement of multiple realisations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>o Applicability for various scales</td>
<td></td>
</tr>
<tr>
<td>Geomechanical DFNs</td>
<td>Palaeostress conditions, rock and fracture mechanical properties</td>
<td>• Linking geometry with physical mechanisms</td>
<td>• Uncertainties in input properties and tectonic conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Correlation between different fracture attributes</td>
<td>• Large computational time</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Negligence of hydraulic, thermal and chemical processes</td>
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<tr>
<td>Geomechanical modelling</td>
<td></td>
<td></td>
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<tr>
<td>Continuum models</td>
<td>Equivalent material properties</td>
<td>• Simplicity of geometries</td>
<td>• No consideration of fracture interaction, block displacement/interlocking/rotation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Efficient calculation</td>
<td>• Complexity in deriving equivalent material parameters and constitutive laws</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Suitability for large-scale industrial applications</td>
<td>• Valid only if an REV exists</td>
</tr>
<tr>
<td>Block-type &amp; particle-based discrete models</td>
<td>Material properties for both fractures and rocks, damping coefficient, bonding strengths</td>
<td>o Explicit integration of DFNs</td>
<td>o Limited data on joint stiffness parameters</td>
</tr>
<tr>
<td></td>
<td></td>
<td>o Simple particle/grain bonding logic</td>
<td>o Calibration of input particle bonding properties</td>
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<tr>
<td></td>
<td></td>
<td>o Integrated constitutive laws for rocks/fractures</td>
<td>o No fracture mechanics principle</td>
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<td></td>
<td></td>
<td>o Capturing the interaction of multiple fractures</td>
<td>o Large computational time</td>
</tr>
<tr>
<td>Hybrid FEMDEM models</td>
<td>Material properties for both fractures and rocks, fracture energy release rate, damping coefficient</td>
<td>• Explicit integration of DFNs</td>
<td>• Calibration of fracture energy release rates</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Fracture propagation is based on both the strength criterion and fracture mechanics principles</td>
<td>• Large computational time</td>
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<tr>
<td></td>
<td></td>
<td>• Integrated constitutive laws for rocks/fractures</td>
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<tr>
<td></td>
<td></td>
<td>• Capturing the interaction of multiple fractures</td>
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4. A geomechanical model for simulating rough natural fractures

The geomechanical model for simulating natural fractures in this thesis is based on the combined finite-discrete element method (FEMDEM) [Munjiza, 2004]. The FEMDEM method has been extensively developed and applied during the past decades and has proven its strong capability in handling large strain deformation, multi-body interaction, fracturing and fragmentation [Elmo et al., 2013; Latham et al., 2013; Lisjak and Grasselli, 2014]. However, to model rock fractures associated with intrinsic surface asperities, an extension of the FEMDEM model is needed in order to capture the complex non-linear, scale-dependent strength and deformation behaviour of natural fractures [Bandis et al., 1981, 1983; Barton et al., 1985].

The FEMDEM model represents a fractured rock using a fully discontinuous mesh of triangular (in 2D) or tetrahedral (in 3D) finite elements with their interfaces connected by joint elements. There are two types of joint elements: unbroken joint elements inside the matrix and broken joint elements along existing fractures. The propagation of new fractures is captured as the transition of unbroken joint elements to broken ones in an unstructured grid. The joint constitutive model (JCM) proposed by Bandis et al. [1983] and Barton et al. [1985] based on the empirical parameters of joint roughness coefficient (JRC) and joint compressive strength (JCS) has been implemented into the 2D/3D FEMDEM framework. The coupling between the JCM and FEMDEM fields is achieved with respect to both stress and displacement solutions, so that the aperture calculation accounts for both fracture interaction-induced separations and roughness-controlled openings. The non-linear shear strength of fractures is captured by updating the frictional force computation in the FEMDEM iterations with the mobilised friction coefficient derived from the JCM calculation. The effective fracture sizes (i.e. between fracture intersections) are calculated through a binary (in 2D) or ternary (in 3D) tree search of connected broken joint element chains so that the scale-dependent fracture wall properties (i.e. JRC and JCS) can be assigned to individual fractures with different lengths.

![Fig. 3](image-url)  
**Fig. 3** Verification of the numerical model based on a direct shear test of different sized fracture samples under a constant normal stress: (a) shear stress-shear displacement curves (the oscillatory effect reported in the thesis as shown by the dashed lines has been largely reduced by better mimicking the quasi-static condition using a periodic loading [Lei et al., 2016]), and (b) dilational displacement-shear displacement curves obtained from the numerical simulations and empirical solutions.

The JCM-FEMDEM model is verified by the consistency between the numerical results and empirical solutions for a direct shear test of different sized fracture samples (Fig. 3). The rough fractures exhibit significant non-linear shear strength behaviour with the maximum value reached at the peak shear displacement, beyond which the strength gradually decreases to the residual value (Fig. 3a). During the shearing process, the fractures
exhibit slight contraction in the pre-peak stage and considerable dilation in the post-peak stage (Fig. 3b). As the fracture size increases, a transition from a “brittle” to “plastic” shear failure mode occurs with a reduced peak shear strength, an increased peak shear displacement and an enlarged dilational displacement. The JCM-FEMDEM model that simulates the complex normal and shear deformations of rough fractures without representing their roughness profiles explicitly tends to be advantageous in solving large-scale problems.

5. Hydromechanical modelling of 2D fracture networks

The JCM-FEMDEM model is applied to simulate the effects of in-situ stresses on the deformation and fluid flow in 2D fracture networks, which include a 1.5 m × 1.5 m analogue fracture network (AFN) mapped based on a limestone outcrop at the Bristol Channel Basin [Belayneh et al., 2009] and its random discrete fracture network (DFN) equivalents. This fracture system contains two distinct cross-cut sets of layer-normal joints with generally straight traces, and is therefore considered well suited to being represented by stochastic DFNs whose performance for hydromechanical predictions, however, may need further assessments. Ten DFN realisations were generated based on the measured statistics of the AFN, i.e. fracture orientations, lengths and inhomogeneous spatial distributions.

![AFN and DFN](image)

**Fig. 4** Stress distribution in the AFN and one of its DFN equivalent under in-situ stresses applied at different angles.

A series of plane strain numerical experiments is designed with the far-field effective stresses ($\sigma'_1 = 10$MPa, $\sigma'_3 = 5$MPa) applied at a range of angles (0°, 30°, 60°, 90°, 120° and 150°) to the AFN and DFNs (Fig. 4). The models adjust to a deformed state under the imposed boundary stresses and exhibit significant stress heterogeneity, which is controlled by both the fracture network geometry and the in-situ stress condition. A comprehensive comparison between the AFN and DFNs is made with respect to various geomechanical responses such as shear displacement, crack propagation, hydraulic aperture and network connectivity. The AFN and DFNs exhibit certain similarity in their average response to the change of the in-situ stress orientation, whereas DFNs tend to accommodate larger shear displacement, more crack propagation, wider hydraulic apertures and more intersection nodes (Fig. 5). The discrepancy may be attributed to the oversimplification of the DFN geometries in representing natural fractures involving complex curvature, spacing and clustering features.
Fig. 5 Variation of fracture network properties with the change of the in-situ stress orientation: (a) average shear displacement, (b) length of new fractures (c) average hydraulic aperture, and (d) number of “T” and “X” intersection nodes.

Fig. 6 The equivalent permeability components $k_{xx}$ in the x direction and $k_{yy}$ in the y direction, and the permeability anisotropy ratio $k_{xx}/k_{yy}$ of the AFN and DFNs with the matrix permeability $k_m$ assumed to be 0.1, 1 and 10 mD.
The equivalent permeability of the stressed 2D fractured rocks is derived from single-phase steady state flow simulations based on the hybrid finite element and finite volume method [Geiger et al., 2004]. As shown in Fig. 6, the equivalent permeability is much larger than the assumed matrix permeability (i.e. $k_m = 0.1, 1$ or $10$ mD), implying that fractures play a dominant role for fluid flow across the fractured rock. The mean permeability of the multiple DFNs shows a reasonably good match with that of the AFN in the x direction associated with an initially good connectivity state, whereas a significant discrepancy was observed in the y direction with a connectivity close to the critical percolating state (more sensitive to geomechanical effects). The high variability in the DFN simulation results (error bar of ± ~30-50%) suggests that large uncertainty may exist in the random DFN approach, especially when the matrix is less permeable (e.g. $k_m = 0.1$ mD) and flow is more dominated by fractures. The quality of DFNs for hydromechanical modelling of fractured rocks is considered to be governed by the accuracy in representing geologically-formed network geometries and geomechanically-controlled fracture apertures.

6. Upscaling of 2D fracture network models

Geomechanical modelling of the development of fracture patterns and apertures achieved on a scale spanning the laboratory specimen to perhaps a few meters is becoming relatively accurate with the FEMDEM simulation. Many important geological phenomena can be captured including the reactivation of pre-existing fractures, the propagation of new cracks and the variation of fracture apertures. Due to the limits of processing power, it is currently impossible to directly extend this accuracy to macroscale computations. Hence, upscaling is required to estimate important subsurface properties of naturally fractured rocks at larger scales based on models established at a smaller scale. Disordered geological media often exhibit significant self-similarity and scaling behaviour [Barton, 1995; Odling, 1997; Bour et al., 2002], the understanding of which opens the possibility that hydromechanical properties of a macroscale fractured rock may be estimated based on the characterisation of its crucial features from a relatively smaller sample. The scope of this study is chosen to be on the in-situ scale (say, 1-100 m), where flow is often dominated by fractures [Clauser, 1992], and to focus on the mechanisms by which the permeability of fractured rocks may vary with the modelling scale over this range.

![Fig. 7](image_url)

**Fig. 7** (a) The 6 m × 6 m outcrop pattern for measuring scaling properties, (b) the 2 m × 2 m source cell pattern including censored and uncensored fractures for geomechanical modelling and network growth, and (c) the growth lattice for extrapolating fracture networks progressively into larger domains based on (d) a recursive scheme.
The scaling properties of a 6 m × 6 m natural fracture system (Fig. 7a) are examined in terms of spatial organisation, lengths and connectivity using fractal geometry and power law relations. The fracture pattern is observed to be nonfractal with the fractal dimension \( D \approx 2 \) (i.e. homogeneous space filling), while its length distribution tends to follow a power law with the exponent \( \alpha \approx 2.37 \). For this network with \( \alpha < D+1 \), the critical system size (or the connection length) \( L_c \) corresponding to the percolation threshold is calculated to be \( \sim 0.80 \) m, above which the fracture network is expected to be well-connected due to the increased network connectivity with scale [Davy et al., 2006]. A smaller domain with size \( L = 2 \) m (Fig. 7b) is used for FEMDEM simulation to generate a realistic distribution of fracture apertures and shear displacements under a hydrostatic or deviatoric stress condition. This smaller pattern with \( L = 2 \) m also serves as the source for network upscaling with its validity examined through a comparison with the original larger pattern with \( L = 6 \) m.

By assuming the fracture pattern repeats itself in progressively larger and larger Euclidean space, a novel upscaling scheme is developed to extrapolate the geologically-mapped fracture geometry together with its stress-dependent, spatially-variable displacement attributes (i.e. fracture aperture and shear displacement) into larger scales using a recursive growth lattice (Fig. 7c & d). There are two types of cells in a growth lattice: the source cell that is the reference for network repetition, and the growth cell that is a clone of the source cell sharing common geostatistics. The fractures are classified into censored (partially sampled) and uncensored (completely observed) types (Fig. 7b). Methods of statistics are applied to the source pattern to interpret its topological complexity in a quantitative way. The locations of censored fractures are measured based on the distribution of censoring nodes which truncate the partially sampled fractures at the source cell boundary. The spatial organisation of uncensored fractures is characterised by the distribution of their barycentres as well as the exclusion radius and spacing parameters. The characteristics of individual fractures are also statistically quantified with respect to orientation, length, segmentation, curvature, shear displacement and aperture. The growth of censored and uncensored fractures in a growth cell is implemented in different ways due to their distinct geostatistical features. A censored fracture in a growth cell evolves from a nucleus located on the lattice edge (Fig. 8a) and propagates following a random walker (Fig. 8b), while an uncensored crack hatches from the barycentre randomly seeded inside the cell (Fig. 8c) and propagates as two synchronised walkers jogging towards opposite directions (Fig. 8d).

Fig. 8 (a) Nucleation of censored fractures by seeding censoring nodes along the edges of a growth lattice, (b) propagation of a censored fracture from a censoring node traced by a random walker, (c) nucleation of uncensored fractures by a point packing process, and (d) propagation of an uncensored fracture from its barycentre captured by two synchronised random walkers.
To examine the validity of the growth network for representing larger fracture geometries, a comparison is made at a system scale of \( L = 6 \) m between the original analogue fracture network (AFN) from outcrop mapping (Fig. 9a), ten realisations of growth fracture network (GFN) extrapolated from the central \( L = 2 \) m source pattern (Fig. 9b), and ten realisations of purely random Poisson DFNs (Fig. 9c). The advantages of the proposed growth networks are highlighted through a qualitative visual comparison (Fig. 9) and a quantitative measurement of the fracture spacing distribution (Fig. 10).

![Fig. 9 Fracture patterns (domain size \( L = 6 \) m) of (a) the analogue fracture network (AFN), (b) one of the ten growth fracture network (GFN) realisations, and (c) one of the ten Poisson discrete fracture network (DFN) realisations.](image)

![Fig. 10 Spacing distribution of the analogue fracture network (AFN), growth fracture networks (GFNs), and Poisson discrete fracture networks (DFNs), measured by twenty scanlines along (a) the y direction and (b) the x direction, respectively.](image)

Multiscale growth networks with stress- and scale-dependent apertures are constructed using the recursive growth scheme with the important natural fracture characteristics (e.g. non-planarity, segmentation, local clustering and length scaling) preserved (Fig. 11). The equivalent permeability of the growth networks is derived from single-phase flow simulations with the matrix permeability assumed to be \( 1 \times 10^{-15} \) m\(^2\). As shown in Fig. 12, with the increase of the scale, the permeability of the fractured rock in the deviatoric stress scenario displays an upward trend at the small and intermediate scales (<10-20 m) and a continued downward trend at larger scales (>20 m), whereas the permeability in the hydrostatic case mainly shows a downward trend except a slight increase in the y direction at the small scale (<10 m). Fracture networks under the deviatoric stress condition appear to be more permeable than those under the hydrostatic condition due to the effects of shear dilations in response to differential stresses.
Two factors may dominate the permeability scaling trend: (i) the length exponent $a$ that governs the connectivity scaling of a fracture population [Berkowitz et al., 2000; Darcel et al., 2003], and (ii) the scaling exponents of fracture apertures and shear displacements which control the transmissivity scaling of each individual fracture [de Dreuzy et al., 2002]. For the studied case of $2 < a < D+1$, with the increase of domain size $L$, the number of fractures larger than $L$ (i.e. traversing fractures) increases as $-L^{-a+1}$ [Davy et al., 2006], whereas the relative percentage of such fractures decreases as $-L^{-a-D+1}$. Thus, a global downward trend might be expected for rock permeability at large scales [Renshaw, 1998; Klimczak et al., 2010]. The flow behaviour is also significantly affected by the distribution of variable apertures, which leads to various fluid flow structures [de Dreuzy et al., 2001b] and permeability scaling trends [Klimczak et al., 2010]. Under a higher in-situ stress ratio, longer fractures play a more important role for fluid migration due to their lower resistance [Tsang and Neretnieks, 1998] in association with wider apertures that are correlated with fracture length. Hence, at smaller scales, an increased permeability occurs in the deviatoric stress case attributed to the considerable contribution from long fractures. However, a global decreasing trend is inevitable due to the decreasing proportion of traversing fractures at larger scales, where shorter fractures tend to take a heavier role in fluid flow. In the hydrostatic stress case, the equivalent permeability mainly declines with the increased scale, because the slightly scaled apertures with no shear-induced dilation do not endow long fractures with highly conductive capability compared to the decreased relative frequency of long fractures whose length follows the power law.

The trend of rock permeability with scale may be further explained by the flow structure transition zone between the connecting scale and the channelling scale [de Dreuzy et al., 2001a, 2001b; Davy et al., 2006].
connecting scale $L_c$ (or the connection length) is where the fracture network shifts from disconnected to connected, while the channelling scale $\xi$ (i.e. the correlation length in the percolation theory) is where the flow structure transforms from extremely channeled to distributed. For growth networks in the deviatoric stress case (Fig. 13), the connection length $L_c$ seems to be at a scale <2 m, which is consistent with the predicted value of ~0.80 m before, and the channelling scale $\xi$ is at 20-50 m. Within the transition zone (i.e. the system size is between $L_c$ and $\xi$), the flow structure is made up of a number of quite independent, multi-path, multi-segment channels [Tsang and Neretnieks, 1998], under the preference of fluid to flow in least resistance paths through the disordered network of finite-sized, curved fractures. This tortuosity feature has significant impact on the flow properties [Ronayne and Gorelick, 2006] and may become even more crucial when the considered rock volume exceeds the channelling scale $\xi$, beyond which the percentage of domain-sized fractures decreases and flow begins to exhibit dispersive behaviour (like in a homogeneous porous medium) [de Dreuzy et al., 2001a; Davy et al., 2006]. A comparison with the analytical solution of the equivalent permeability $k_{\text{harm}}$, $k_{\text{arithm}}$, $k_{\text{geom}}$ based on the measured harmonic, arithmetic or geometric mean apertures, respectively, reveals that the numerically derived permeability is well bounded by the harmonic and arithmetic values, while the median trend is better tracked by the geometric one (Fig. 12).

![Fig. 13 Flow structure transition from extremely channelled to distributed in multiscale growth networks under the deviatoric stress condition (boxes illustrate the main pathways of the flow structure).](image)

Highly conductive fractures with long lengths and wide apertures capable of transmitting fluid across long distances seem to behave more like an “in parallel” connected network [Leung and Zimmerman, 2012], so $k_{xx}$ is better captured by the upper arithmetic bound at smaller scales, where the channels formed by very long fractures dominate the flow. However, at larger scales, fluid has to migrate through less conductive branches to reach the opposite boundary due to the proportional reduction of longer fractures, which makes the fracture population act more like an “in series” connected network and $k_{xx}$ tends to approach the lower harmonic bound. The equivalent permeability in the y direction $k_{yy}$ mainly exhibits closer values to the lower limit due to the inherent zigzag feature of the flow structure. Indeed, the mechanism of network alteration from “parallel” to “series” is equivalent to the essence of flow structure transition from “channelled” to “distributed”. The permeability magnitudes under the prescribed hydrostatic and deviatoric stresses tend to converge at larger scales but with the intrinsic anisotropy
retained. At even larger scales (e.g. >100 m), the fractured rock may behave like a porous medium [Long et al., 1982] with a lower REV permeability conjectured. However, the repetition assumption may not be valid at that scale since many complex larger-scale factors (e.g. seismically visible faults) will be involved [Clauser, 1992], which is beyond the current scope.

7. Hydromechanical modelling of an idealised 3D persistent fracture network

The stress effects on the permeability of fractured rocks have been widely investigated based on 2D fracture network models in the past decades [Zhang et al., 1996; Min and Jing, 2004; Baghbanan and Jing, 2008; Latham et al., 2013]. However, the 3D nature of fluid flow in fractured rocks under polyaxial (i.e. true-triaxial) stress conditions remains poorly understood. In this research, the 3D JCM-FEMDEM model is applied to investigate the flow heterogeneity in an idealised 3D persistent fracture network caused by both the fracture-scale roughness effect and the network-scale fracture interactions under polyaxial in-situ stresses.

The discontinuity system involves three orthogonal sets of persistent fractures with one horizontal set of bedding planes and two vertical sets oblique at 45° to the lateral boundaries, on which the far-field horizontal stresses are imposed. All fractures are assumed through-going, tending to provide an upper limit for rock deformability and permeability. The dispersion of fracture orientation is omitted to avoid the numerical difficulty in treating high aspect ratio elements caused by intersection between sub-parallel fractures from the same set. This idealised persistent fracture network might be representative of some special scenarios of highly fractured “non-strata bound” sedimentary rocks. The rock sample (0.5 m × 0.5 m × 0.5 m) is designed to be surrounded by a hollow-box shaped buffer zone with a reduced Young’s modulus to provide a semi-free displacement boundary constraint for accommodating potential large slipping in such a persistent system.

![Fig. 14](image)

(a) The fractured rock is loaded by two consecutive phases of polyaxial stress conditions and (b) exhibits strong heterogeneity in stress and displacement distributions.

The fractured rock is loaded in two consecutive phases (Fig. 14a): an isotropic stress field with \( \sigma_x' = \sigma_y' = \sigma_z' = 5 \) MPa for consolidation (Phase I), and a series of deviatoric stress conditions with a fixed \( \sigma_z' = 5 \) MPa, various \( \sigma_y' = 5-20 \) MPa and an increased \( \sigma_y' = 10 \) MPa (Phase II). Significant heterogeneity in stress and displacement distributions is generated when the stress ratio \( \sigma_y'/\sigma_x' \) is high (Fig. 14b). The deformation of the fractured rock under a high stress ratio results in a highly variable aperture field in single fractures (Fig. 15). Very large apertures are clustered in some local areas, which seem to be connected and form a slightly diverted vertical channel from the top to the bottom of the domain.

The equivalent permeability of the fractured rock under various polyaxial stress conditions is derived from steady state single-phase flow simulations with the matrix permeability \( k_m = 1 \times 10^{-15} \) m\(^2\). The increased stress ratio of \( \sigma_y' \) to \( \sigma_x' \) leads to considerable increase over several orders of magnitude in the diagonal of the permeability tensor, i.e. the components, \( k_{xx}, k_{yy}, \) and \( k_{zz} \) (Fig. 16a). A transition regime with steep permeability increase occurs when the stress ratio is approaching the critical threshold (i.e. 3.1 given that the friction coefficient equals to 0.6 [Zoback, 2007]). The permeability tensor also changes from isotropic to highly anisotropic with the
increase of $\sigma'_y/\sigma'_x$ due to the deviatoric stress acting with respect to the favourably oriented vertical fractures, resulting in zigzag-shaped localised pathways and very high permeability in the subvertical direction (Fig. 16b).

Fig. 15 Distribution of hydraulic apertures within a single fracture of the fracture network under a polyaxial stress condition of $\sigma'_x = 5 \text{ MPa}$, $\sigma'_y = 15 \text{ MPa}$ and $\sigma'_z = 10 \text{ MPa}$.

Fig. 16 (a) Equivalent permeability of the fractured rock under various polyaxial in-situ stress conditions. (b) The permeability tensor and flow pathways of the fracture network under the stress conditions with $\sigma'_y/\sigma'_x = 1$ and 3.

8. Hydromechanical modelling of a realistic 3D fracture network

The 3D JCM-FEMDEM model is further used to investigate the geomechanical behaviour of a fractured limestone layer embedded with realistic joint sets involving curvature, intersection, abutment and termination features (Fig. 17). The 3D fracture system is constructed by extruding a 2D outcrop pattern (2 m × 2 m) of a limestone bed by the layer thickness of 0.1 m. This fracture network exhibits a ladder structure consisting of a “through-going” joint set abutted by later-stage short fractures. A series of in-situ stress conditions is designed to explore the following horizontal stress ratios: $\sigma'_y/\sigma'_x = 1/3$, $1/2$, 1, 2, and 3 (Fig. 17).
A 3D fractured limestone layer is loaded by various polyaxial stress conditions.

<table>
<thead>
<tr>
<th>Case</th>
<th>$\sigma'_x$ (MPa)</th>
<th>$\sigma'_y$ (MPa)</th>
<th>$\sigma'_z$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>10</td>
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<td>C</td>
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<td>D</td>
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</tr>
<tr>
<td>E</td>
<td>15</td>
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<td>10</td>
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</tbody>
</table>

$2 \text{ m} \times 2 \text{ m} \times 0.1 \text{ m}$

The fractured rocks arrived at equilibrium and exhibit distinct stress distribution patterns under different polyaxial stress conditions (Fig. 18). The distribution of local maximum principal stresses under an isotropic horizontal stress condition (i.e. $\sigma'_x = \sigma'_y = 5 \text{ MPa}$) is quite uniform and dominated by the overburden stress (i.e. $\sigma'_z$.
= 10 MPa). With the increase of the stress ratio (either \( \sigma'_x/\sigma'_y \) or \( \sigma'_y/\sigma'_x \)), stress heterogeneity begins to emerge and escalate, with the high stress zones aligning the direction of the far-field maximum horizontal stress. Furthermore, the increased horizontal stress ratio also results in new crack propagation and aperture variability (Fig. 19). Thus, the vertical flow structure changes from uniformly distributed to highly localized as the horizontal stress ratio increases (Fig. 20). The magnitude and anisotropy of the equivalent permeability also varies significantly with respect to the change of the in-situ stresses (Fig. 21). The distinct stress-dependent variation of the equivalent permeability in the x and y directions (more sensitive to an increased stress ratio of \( \sigma'_y/\sigma'_x \) than to an increased ratio of \( \sigma'_x/\sigma'_y \)) is attributed to the inherent anisotropy of the joint network geometries. The bed-normal permeability \( k_{zz} \) is much more sensitive to the change of stress loading than \( k_{xx} \) and \( k_{yy} \). The results demonstrate that both the magnitude and orientation of the far-field stresses have significant influence on the permeability of the fractured layer embedded with an anisotropic joint network.

![Vertical flow pathways of the joint network under different polyaxial stress conditions](image)

**Fig. 20** Vertical flow pathways of the joint network under different polyaxial stress conditions (note the flow arrow sizes indicating local flux magnitudes in Case C-E are scaled down by a factor 10 times the one in Case A & B).

![Variations of the equivalent permeability](image)

**Fig. 21** Variations of the equivalent permeability of the fractured layer under (a) an increased \( \sigma'_y \) while \( \sigma'_x = 5 \text{ MPa} \), or (b) an increased \( \sigma'_x \) while \( \sigma'_y = 5 \text{ MPa} \).
9. Application study of excavation damaged zone

Subsurface rocks embedded with natural fractures are often encountered in engineering excavations for tunnel and cavern construction, hydrocarbon extraction, mining operations and geological disposal of radioactive waste. Underground excavations that perturb the rock mass from an originally equilibrated state can engender stress redistribution and trigger the formation of excavation damaged zone (EDZ) [Tsang et al., 2005]. Previous EDZ numerical studies mainly focused on fracturing in intact rocks, while only a few attempts have been made to address the effects of pre-existing discontinuities. The JCM-FEMDEM model that can capture both the reactivation of pre-existing fractures and the propagation of new cracks is used to simulate the EDZ evolution around a tunnel excavation in a crystalline formation.

The numerical experiment of a hypothetical repository is based on the site characterisation of a Ordovician volcaniclastic rock at the Sellafield area, Cumbria, UK [Nirex, 1997a, 1997b]. Four sets of fractures were observed in the field and the fracture lengths tend to follow a power law distribution (Fig. 22a). A DFN network is generated through a Poisson process with the four fracture sets assumed to have equal density. Two 20 m × 20 m 2D cross-sections (i.e. DFN1 oriented at 340º and DFN2 oriented at 250º, from the North) are chosen corresponding to the plane defined by either the maximum ($S'_h$) or minimum ($S'_h$) horizontal stress with the vertical stress ($S'_v$) (Fig. 22b). The circular tunnel has a diameter of 2 m and is placed at the centre of the domain. The response of the fractured rock to in-situ stresses and excavation perturbations is simulated for various tunnel depth scenarios (i.e. 250 m, 500 m and 1000 m) through multiple sequential deformation-solving phases: (i) force equilibration under the geological in-situ stress condition, (ii) central core relaxation during the excavation, (iii) physical removal of rocks inside the tunnel after the excavation, and (iv) damage evolution around the unsupported opening.

Fig. 22 (a) Distribution of fracture lengths mapped at Sellafield that can be fitted by a power law cumulative distribution (after [Blum et al., 2005]), and (b) the 20 m × 20 m DFNs generated in the cross-section plane oriented at 340º (DFN1) and 250º (DFN2) from the North (dashed circles represent the tunnels advancing in two different directions).

For DFN1 at the 1000 m depth (Fig. 23a), the fractured rock exhibits a homogeneous stress distribution under the initial in-situ stress condition which is close to isotropic ($S'_h/S'_v = 1.17$). With the relaxation of core rocks, stress concentrations begin to appear in the fictitiously softening materials as well as the rocks surrounding the tunnel. After the removal of the rocks inside the tunnel, the model continues to solve for the consequent EDZ
evolution around the man-made opening, i.e. the zone where irreversible deformation involving new crack propagation has developed. An interior low stress zone (stress loosing zone) is formed surrounding the tunnel boundary, where intensive rock mass failure develops as a result of structurally-controlled kinematic instability (e.g. key blocks) and stress-driven brittle fracturing (e.g. wing cracks). The stress loosing zone seems to have a long axis along the direction of the in-plane minimum principal stress (i.e. $S'_v$). A self-organised exterior high stress zone (stress arching zone) is promoted at a certain distance to the tunnel periphery, where compression arches seem to evolve along the direction of the in-plane maximum principal stress (i.e. $S'_h$). In contrast, the DFN2 model at the 1000 m depth exhibits significant heterogeneity under the initial in-situ stresses (Fig. 23b). After the removal of rocks in the tunnel, a stress loosing zone is created around the excavation and also tends to follow the direction of the in-plane minimum principal stress (i.e. $S'_v$). An exterior stress arching zone is vertically formed along the in-plane maximum principal stress (i.e. $S'_h$), especially at the right hand side of the tunnel (the marked asymmetry). More interestingly, the high-stress contours of these arching zones seem to be microscopically constrained by the structures of pre-existing fractures.

![Fig. 23](image)

Fig. 23 Damage evolution around the tunnel excavation in the 20 m × 20 m fractured rock embedded with the (a) DFN1 or (b) DFN2 at the depth of 1000 m.

Fig. 24 shows the near-field fracture development around the tunnel excavation in the two DFN models at various depths. At the 250 m depth, quite few new cracks emerge in both networks and the rock can almost remain stable except slight structurally-controlled falling of rock pieces. At the 500 m depth, slightly more new cracks are generated in both DFN networks. However, for the scenario of 1000 m depth, extensive tension-dominated new cracks accompanied by a few shear-dominated ones are created. The propagation of these new cracks tends to follow the direction of the in-plane maximum principal stress in each DFN model, i.e. horizontally in DFN1 and vertically in DFN2. The new cracks in DFN1 are concentrated in the rock above the tunnel top or under the invert (Fig. 24c), whereas the fracturing in DFN2 mainly occurs in the lateral space (Fig. 24f). It is found that excavation in the condition with a higher far-field maximum principal stress tends to generate more irreversible damage in the host rock. Based on the collapsed state of the rock mass, the shape and depth of the failure zone can be determined, which are useful for the support system design (e.g. lining thickness, bolt length and position). The results of this study have important implications for designing stable underground openings for nuclear waste repositories and other engineering facilities which are intended to generate minimal damage in host media.
Fig. 24 Fracture development at the near field to the excavation boundary in the fractured rocks at different depths, i.e. 250 m, 500 m, and 1000 m.

10. Implications and conclusions

10.1. Implications for rock engineering

(i) A tectonic interpretation was presented to explain the connectivity evolution of a multiscale natural fracture system (Chapter 2). This work proposed an answer to the open question—Are natural fracture networks well or poorly connected? The discussion on the “effective” and “apparent” connectivity has important implications for various rock engineering problems concerned with the percolation state of natural fracture systems such as oil/gas recovery, rock mass stability, and geological disposal of radioactive waste.

(ii) A general-purpose geomechanical simulator was developed to simulate the realistic fracture behaviour under stress loading including non-linear normal deformation, roughness-controlled shear strength and dilatancy, and their non-trivial size effects (Chapter 4). This numerical method, which has been validated against well-established empirical solutions, permits rock engineers to more accurately simulate the geomechanical response of natural fractures and fractured rocks in response to in-situ stresses or engineering perturbations.

(iii) The stochastic Poisson DFN model, which has been commonly used in the rock mechanics community, was thoroughly examined for their validity and quality in representing natural fractured systems (Chapter 5). The results provided useful references for rock engineers about the uncertainty of stochastic DFN modelling.

(iv) A novel upscaling approach was proposed for simulating larger-scale properties of fractured rocks including their fracture geometry, aperture variability, and equivalent permeability (Chapter 6). This new method can be used by rock engineers to predict scale- and stress-dependent behaviour of geological formations in hydrocarbon, geothermal or geodisposal systems.

(v) A workflow for integrating geological information, simulating stress perturbation, deriving aperture distribution, and calculating equivalent permeability of fractured rocks was developed for both 2D and 3D problems (Chapters 5, 7 & 8). Such a workflow provides a very useful practical tool for rock engineers to solve real problems.
(vi) The technique of modelling EDZ evolution in fractured formations permits rock engineers to characterise the complex interactions between pre-existing fractures and new propagating cracks under excavation-induced perturbations. The results have important implications for designing underground openings for radioactive waste repositories, mining operations, and public transportations.

10.2. Conclusions

To sum up, this thesis presented a systematic study of the geometry, geomechanics and fluid flow properties of natural fracture networks. The complexity of natural fractures with respect to hierarchical topologies and underlying mechanisms was investigated through a study of the statistics and tectonism of a multiscale fracture system. To simulate the complex geomechanical behaviour of natural fractures associated with intrinsic surface asperities, a joint constitutive model (JCM) was implemented into the framework of the finite-discrete element method (FEMDEM). The JCM-FEMDEM model can calculate the stress/strain fields of intact rocks, capture the mechanical interactions of multiple blocks, characterise the non-linear deformation of rough fractures and mimic the propagation of new cracks. This numerical model has been applied to simulate the geomechanical behaviour of various 2D and 3D fracture networks at metric scales with the consequences on their equivalent permeability further analysed. To estimate the hydromechanical properties of a natural fracture network at larger scales, a novel upscaling approach employing discrete-time random walks in a recursive self-referencing lattice was developed to extrapolate fractures together with their stress- and scale-dependent apertures into larger domains. Distinct permeability scaling behaviour was observed for fracture networks under different in-situ stress conditions. The capability of the JCM-FEMDEM model was further demonstrated through an example of modelling the damage evolution around an excavation in a geological formation embedded with pre-existing natural fractures. The research findings of this thesis illustrate the importance of realistic fracture network representation and systematic geomechanical simulation for modelling the hydromechanical behaviour of naturally fractured rocks.

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