Lawrence Berkeley National Laboratory

Recent Work

Title

A micromechanical hydro-mechanical-damage coupled model for layered rocks considering multi-scale structures

Permalink

<https://escholarship.org/uc/item/1nf9n7t9>

Authors

Liu, W
Zheng, L
Zhang, Z
et al.

Publication Date

2021-06-01

DOI

10.1016/j.ijrmms.2021.104715

Peer reviewed

A micromechanical H-M-D coupled model for layered rocks

considering multi-scale structures

Abstract: An anisotropic H-M-D coupled model was established for saturated layered rocks containing arbitrarily-distributed cracks of smaller scales and orientated bedding planes of much larger scales in the framework of thermodynamics. The impacts of anisotropic damage growth and frictional sliding of cracks and shear sliding and dilatancy of bedding planes, as well as the interaction between cracks and bedding planes on the deformation and permeability of layered rocks in coupled HM loading conditions, are simultaneously considered in the proposed model. Numerical implementation of the nonlinear coupled model was developed based on the TOUGHREACT, which is a well-established simulator for multiphase fluid flow and reactive transport analysis. The proposed model was first validated with laboratory water injection test results on rock blocks, and then used to study the effects of injection rates, in-situ stresses and existed bedding planes on fluid injection processes at the field scale, demonstrating the importance to consider the variation of multi-scale structures for better understanding the coupled HM responses in layered rocks.

Key words: Layered rocks; Anisotropic damage; Hydro-Mechanical coupling; Micromechanics; Permeability variation

1. Introduction

Couplings between the hydrological and mechanical processes in rock mass play a crucial role in various engineering activities (Chen et al. 2007, Figueiredo et al. 2015, Kim et al. 2015, Guayacán-Carrillo et al. 2017, Cañamón et al. 2019, Yi et al. 2019, Gao & Ghassemi 2020, Wu et al. 2020), such as underground resources exploitation and utilization, radioactive waste disposal, CO₂ geologic sequestration, underground hydraulic tunnels or caverns, etc. Among these engineering applications, layered rocks are usually encountered due to the inherent anisotropy of rock masses commonly distributed on earth (Barton & Quadros 2015). Being a highly structural geological media, the layered rocks are comprised of rock blocks separated by oriented macroscopic

discontinuities, such as bedding planes, lineation, persistent joints, foliation, or schistosity, which significantly influence the anisotropic permeability and deformation. The Hydro-Mechanical (HM) properties of layered rocks are essentially controlled by the pores and cracks of smaller scales within rock blocks and oriented macroscopic discontinuities of much larger scales, and as the geometries of these void system change, the deformation and flow behaviors in layered rocks under HM loading change accordingly. Therefore, the HM responses of layered rocks are in nature scale-dependent and deformation-dependent. Owing to the multi-scale void system and complex interactions between the hydraulic and mechanical behaviors, developing a reliable numerical method for the coupled processes in layered rocks remains an issue of great challenges.

In consideration of the oriented macroscopic discontinuities, many anisotropic elastoplastic constitutive models have been proposed by treating the layered rocks as transversely isotropic media. The elastoplastic models are mainly obtained from the extension of the isotropic formulations by introducing transversely isotropic Hooke's law for elasticity, orientation dependence of anisotropic failure criterion for plasticity (Chen et al. 2012, Ismael et al. 2019, Wang et al. 2019, Forero et al. 2020), and directional-dependent Biot coefficients for poroelasticity (Cheng 1997, Guayacan-Carrillo 2017). In the work done by Guayacan-Carrillo et al. (2017), for instance, a fully coupled anisotropic poroelastic model was developed with the accounting of transversely isotropic elastic stiffness tensor, two different Biot coefficients in the direction parallel and perpendicular to the plane of isotropy. In these models, the anisotropic deformation and failure characteristics are well captured, but the effect of mechanical deformation on the permeability is rarely considered. The dependence of permeability on the changes in oriented macroscopic discontinuities is usually modeled by separating the deformation of oriented macroscopic discontinuities from that of the equivalent medium (Chen et al. 2007, Wilkins & Qu 2020). However, the above models mainly focus on the influence of oriented macroscopic discontinuities on the deformation, flow, and coupling characteristics, but rarely consider the variation of cracks of smaller scales simultaneously. In the deep-seated environment, the contributions of the crack system to the coupled HM behaviors in layered rocks may be comparable to that of the oriented macroscopic discontinuities due to well-sealed and less density of macroscopic discontinuities under high in-situ stress condition or seriously damaged of cracks in the rock blocks under

engineering disturbance (Liu et al. 2016). In consideration of cracks of smaller scales, the micromechanics-based damage modeling methods have been identified as the excellent approaches for relating the macroscopic behaviors of the material to the microscopic characteristics of cracks with clear physical mechanisms (Zhu & Shao 2017). Although many micromechanics-based damage constitutive models have been proposed to characterize the microcracking behaviors (Zhu et al. 2008, Qi et al. 2016, Zhu & Shao 2017), most studies are limited to mechanical responses, and the variation of bedding plane structure is rarely considered simultaneously. It's of theoretical importance to study the anisotropic H-M coupling models for layered rocks accounting for the variation of multi-scale structures.

In this paper, a Hydro-Mechanical-Damage (H-M-D) coupled model for saturated layered rocks that contain cracks in rock block separated by bedding planes of much large scales is proposed with numerical implementation via adding mechanical process to a multiphase fluid flow, heat and reactive transport code, TOUGHREACT (Xu et al., 2011). Section 2 presents a description of the coupled constitutive model derived from the proposed free enthalpy of saturated layered rocks, the influences of crack initiation and propagation at the microscopic scale, and bedding planes deformation at macroscopic scale on the evolution of deformation and permeability are simultaneously accounted in the proposed model. Computational aspects of the TOUGHREACT-based numerical implementation are discussed in Section 3, in which validation studies are performed against laboratory injection tests on rock block and anisotropic strength experiments on layered rocks. Section 4 provides numerical examples of the proposed model on water injection modeling at field scale addressing the influence of multi-scale structures, followed by conclusions presented in Section 5.

2. Formulation of a H-M-D coupled model

The hydro-mechanical property of layered rocks is essentially controlled by the internal micro-/macro-structures, which are pores and cracks of smaller scales and bedding planes of much larger scales. To accounting the multi-scale structures in model development, the layered rock is represented by the homogeneous elastic solid matrix weaken by randomly distributed cracks and cut by oriented bedding planes. The elastic behaviors of a solid matrix can be obtained by a preliminary homogenization procedure accounting for the presence of pores (Dormieux et al.

2006).

In consideration of the representative volume element (RVE) of layered rocks, Ω (Fig. 1), it contains penny-shaped cracks arbitrarily distributed in rock blocks segmented by a set of parallel bedding planes with negligible aperture compared to average spacing. Let Σ be the uniform macroscopic stress field prescribed on the boundary of the RVE saturated by a fluid pressure p . At the macroscope scale, the bedding planes are modeled as an interface. According to the continuity of stress vector when crossing bedding planes (Chen et al. 2006, Liu 2018)

$$\Sigma = \Sigma^R = \Sigma^J \quad (1)$$

where Σ^R, Σ^J are the macroscope stress tensor of rock block and bedding plane.

Fig. 1 Homogenization of the layered rocks in model development

A two-step homogenization technique is adopted to formulate the H-M-D coupled model of layered rocks to account for the multi-scale structures (Fig. 1). In which the first step is aimed to characterize the macroscopic mechanical responses and deformation-dependent permeability of rock blocks and bedding planes in consideration of their microstructural features (crack system in rock blocks and asperities distributed in rough bedding planes). While the second step is focused on determining the effective mechanical and hydraulic behaviors of layered rocks by accounting the homogenized planar bedding planes embedded in the homogenized rock blocks.

2.1. Free enthalpy of saturated layered rocks

At the first-step homogenization, the rock block with the assumption of uniformly distributed penny-shaped cracks embedded is homogenized by the Eshelby solution-based upscaling procedure. Following the free energy of saturated cracked rocks (Chen et al. 2013, Zhu 2016), the associated free enthalpy W^{R^*} of rock block using the Mori-Tanaka homogenization scheme can be obtained by Legendre-Fenchel transform of the free energy (Zhu et al. 2008, Liu et al. 2016)

$$W^{R^*} = \frac{1}{2}(\boldsymbol{\Sigma} + p\mathbf{B}) : \mathbf{S}^s : (\boldsymbol{\Sigma} + p\mathbf{B}) + \boldsymbol{\Sigma} : \mathbf{E}^c - \frac{1}{8\pi} \oint_{S^2} \left[\frac{H_0}{d} \beta^2 + \frac{H_1}{d} \boldsymbol{\gamma}(\mathbf{n}') \cdot \boldsymbol{\gamma}(\mathbf{n}') \right] dS + p\boldsymbol{\delta} : \mathbf{E}^c + \frac{p^2}{2N} \quad (2)$$

where $\mathbf{E}^c = \frac{1}{4\pi} \oint_{S^2} \beta \mathbf{n}' \otimes \mathbf{n}' + \boldsymbol{\gamma}(\mathbf{n}') \otimes \mathbf{n}' dS$ is the macroscopic strain contributed by the cracks, β

and $\boldsymbol{\gamma}$ are the volumetric averaging of opening and sliding of cracks, $S^2 = \{\mathbf{n}' \mid |\mathbf{n}'| = 1\}$ is the unit

sphere surface accounting for uniform randomly-distributed cracks, $\mathbf{n}'$ denotes the unit normal

vector of randomly-distributed cracks; $\mathbf{S}^s$ is the isotropic elastic compliance tensor of the solid

matrix, which is characterized by its Poisson's ratio ν^s and Young's modulus E^s ; H_0 and H_1 are

two elastic parameters calculated by $H_0 = 3E^s / \{16[1 - (\nu^s)^2]\}$ and $H_1 = H_0(1 - \nu^s/2)$; $\boldsymbol{\delta}$ is the

second-order identity tensor; $\mathbf{n}^j$ is the unit normal vector of bedding planes; $d = N a^3$ is the

microscopic damage variable defined by crack density, N denotes the number of cracks per unit

volume, a is the average radius; $\frac{1}{N}$, $\mathbf{B}$ are the Biot modulus and Biot coefficient tensor of cracked

rock blocks, they are related to the homogenized effective tensor of cracked rocks, with uniform

randomly-distributed cracks in rock blocks an isotropic Biot coefficient tensor is used for

simplification (Xie et al. 2012, Hu et al. 2020), $B = b_0^R \delta$, $\frac{1}{N} = \frac{3(1 - 2\nu^s)(b_0^R - \phi_0^R)}{E^s}$, b_0^R and ϕ_0^R are the Biot coefficient and initial porosity for rock blocks.

Meanwhile, the surfaces of bedding planes at microscope scale are usually rough with different scale of asperities, which play an important role on the deformation behavior. By the first-step homogenization, the parallel plate model with constant aperture is used to geometrically simplify the rough bedding plane, while the influences of roughness on the shear sliding behavior are captured with the equivalent asperity angle (Liu et al. 2016). The macroscopic mechanical behavior of homogenized saturated bedding plane can then be described with the effective stress

$T + b_0^J p n^J$ (Maghous et al. 2013)

$$g = g^e + g^p = (H^J)^{-1} \cdot (T + b_0^J p n^J) + g^p \quad (3)$$

where g is the total displacement jump across the bedding plane, which is comprised of the elastic

component g^e and plastic component g^p ; $T = \Sigma \cdot n^J$ is the total stress acting upon the bedding

plane; $H^J = H_T(\delta - n^J \otimes n^J) + H_N n^J \otimes n^J$ is the second-order elastic tangent stiffness tensor, with

assumption of constant tangential stiffness H_T and normal stiffness H_N ; b_0^J is the Biot coefficient

for bedding planes.

According to the displacement jump of homogenized planar bedding planes presented in Eq. (3), at the second-step homogenization, the macroscopic strain of layered rocks contributed by the bedding planes is described as

$$E^J = E^{Je} + E^{Jp} = \frac{1}{S^J} g^s \otimes n^J = \frac{1}{S^J} (g^e + g^p)^s \otimes n^J \quad (4)$$

where S^J is the average spacing of bedding planes. Accordingly, the free enthalpy W^{Js} contributed

by the bedding planes can be written as (Liu et al. 2016; Liu 2018)

$$\begin{aligned} W^{J*} &= \frac{1}{S^J} \left[\frac{1}{2} (T + b_0^J p n^J) : (H^J)^{-1} : (T + b_0^J p n^J) + (T + b_0^J p n^J) : g^p \right] \\ &= \frac{1}{S^J} \left(\frac{|T^J|^2}{2H_T} + \frac{(T_n^J + b_0^J p)^2}{2H_N} + g^p \otimes n^J : \Sigma + b_0^J p n^J : g^p \right) \end{aligned} \quad (5)$$

where $T_n^J = n^J : \Sigma : n^J$, $T_t^J = n^J : \Sigma : (\delta - n^J \otimes n^J)$ are the normal and tangential components of stress vector acting upon the bedding plane.

Based on the obtained free enthalpy contributed by the cracked rock blocks, Eq. (1), and the bedding planes, Eq. (5), the total free enthalpy W^* of saturated layered rocks can be provided by the second-step homogenization

$$\begin{aligned} W^* &= \frac{1}{2} (\Sigma + pB) : S^s : (\Sigma + pB) + \Sigma : E^c - \frac{1}{8\pi} \oint_{\Gamma} \left(\frac{H_0}{d} \beta^2 + \frac{H_1}{d} \chi(n^t) : \chi(n^t) \right) dS + p \delta : E^c \\ &\quad + \frac{p^2}{2N} + \frac{1}{S^J} \left(\frac{|T^J|^2}{2H_T} + \frac{(T_n^J + b_0^J p)^2}{2H_N} + g^p \otimes n^J : \Sigma + b_0^J p n^J : g^p \right) \end{aligned} \quad (6)$$

2.2 Constitutive model and internal variables evolution

According to the free enthalpy of saturated layered rocks presented in Eq. (6), the macroscopic stress-strain relation and porosity evolution equation can be obtained by the state law of thermodynamics

$$E = \frac{\partial W^*}{\partial \Sigma} = S^s : (\Sigma + pB) + E^c + \frac{1}{S^J} [n^J \otimes (H^J)^{-1} : (T + b_0^J p n^J) + g^p \otimes n^J] \quad (7)$$

$$\phi - \phi_0 = \frac{\partial W^*}{\partial p} = B : S^s : (\Sigma + pB) + \delta : E^c + \frac{p}{N} + \frac{b_0^J (T_n^J + b_0^J p)}{S^J H_N} + \frac{1}{S^J} b_0^J n^J : g^p \quad (8)$$

where ϕ is the porosity of the RVE. Both the influence of cracks in smaller scales and bedding planes in much larger scales on the macroscopic strain and porosity evolution of saturated layered rocks are better characterized with Eqs. (7) and (8). The macroscopic stress can also be described with the macroscopic strain by direct inversion of Eq. (7)

$$\Sigma = C^{RJ} : (E - E^c - E^{Jp} - S^s : pB - \frac{b_0^J p}{S^J H_N} n^J \otimes n^J) \quad (9)$$

where $C^{RJ} = \left[S^J + \frac{1}{S^J} n^J \otimes (H^J)^{-1} \otimes n^J \right]^{-1}$ is the equivalent elastic stiffness tensor for layered

rocks; $E^p = \frac{1}{S^J} n^J \otimes g^p$ is the macroscopic plastic strain contributed by bedding planes.

The constitutive model of layered rocks presented in Eq. (7) under the framework of thermodynamics contains four different types of internal variables, d , β , γ and g^p . The internal variables, d , β and γ are used to characterize the microcracking process in cracked rock blocks, and can be determined by their conjugate thermodynamic forces, F^d , F^β and F^γ

$$F^d(n') = \partial W^* / \partial d = [H_0 \beta^2 + H_1 \chi(n') \cdot \chi(n')] / 2d^2 \quad (10.a)$$

$$F^\beta(n') = \partial W^* / \partial \beta = \Sigma : n' \otimes n' - H_0 \beta / d + p \quad (10.b)$$

$$F^\gamma(n') = \partial W^* / \partial \gamma = n' \cdot \Sigma \cdot (\delta - n' \otimes n') - H_1 \chi(n') / d \quad (10.c)$$

With opened cracks, F^β and F^γ are vanished, internal variables β and γ can be directly obtained by Eqs. 10(b) and 10(c). For closed cracks ($F^\beta \leq 0$), both normal compressive induced cracks closure and sliding dilation induced cracks opening are considered. In which the former normal deformation mechanism is modeled by a hyperbolic function $\beta = F^\beta \beta_0 / (k_0 \beta_0 - F^\beta)$, β_0 and k_0 are the initial closure and normal stiffness of cracks; while the latter sliding dilatancy mechanism is modeled by the associative Mohr-Coulomb criterion $F \geq |F^\gamma| + \tan \phi_c F^\beta$, ϕ_c is the friction angle of cracks. Evolution of d is guided by the following criterion

$$f(F^d, d) = F^d - V(d) = \begin{cases} F^d - V(d_c) \frac{2d/d_c}{1+(d/d_c)^2} & d < d_c \\ F^d - V(d_c) & d \geq d_c \end{cases} \quad (11)$$

where $V(d)$ is the material resistance to further crack propagation, it attains the maximum value $V(d_c)$ at the critical damage d_c . In order to characterize the anisotropic strength characteristics of layered rocks, the interaction between cracks and bedding planes should be considered. Due to the complex interaction between cracks and bedding planes, the microcracking process of cracks is affected by the bedding planes. Two approaches are used here to practically handle the mechanical interaction between cracks and bedding planes. In the first approach the damage resistance of cracks is related to the microstructure tensor of layered rocks by the following expression (Liu et al. 2016)

$$V(d_c) = V_0 \{1 + A_1(1 - 3l_1^2) + b_1[A_1(1 - 3l_1^2)]^2\}^{\frac{1}{2}} \quad (12)$$

where $l_1^2 = \frac{tr(\mathbf{n}^J \otimes \mathbf{n}^J \boldsymbol{\Sigma}^2)}{tr(\boldsymbol{\Sigma}^2)}$; $A_1, V_0, b_1, \frac{1}{2}$ are parameters used for characterizing the interaction between cracks and bedding planes. In Eq. (12), the damage resistance of cracks is closely affected by the normal vector of bedding plane and the generalized loading vector.

The approach presented in Eq. (12) had been proved to be capable of better capturing the anisotropic strength characteristics of slate rocks (Chen et al. 2016; Liu et al. 2016). Due to the existence of bedding planes, the crack damage resistance may also rely on the orientation of cracks, which is not accounted in Eq. (12). To consider this effect, the other approach is formulated with the assumption that the cracks tends to easily propagate with orientation being close to the bedding planes direction (Heng et al. 2015):

$$V(d_c) = V_0(\vartheta + (1 - \vartheta) \frac{2\kappa}{1 + \kappa^2}) \quad (13)$$

where $\kappa = 1 - |\mathbf{n}' \cdot \mathbf{n}^J|$; V_0 and ϑ are the material parameters for characterizing crack-bedding plane interaction. From Eq. (13), one can find that $V(d_c)$ reaches its minimal value $V_0\vartheta$ when the crack orients parallel to the bedding planes ($\mathbf{n}' \cdot \mathbf{n}^J = 1$), and its maximal value V_0 when the crack orients perpendicular to the bedding planes ($\mathbf{n}' \cdot \mathbf{n}^J = 0$).

On the other hand, the plastic deformation $\mathbf{g}^p$ contributed by bedding planes is modeled by the classical saw-tooth model with an equivalent asperity angle α to practically account the influences of multi-order asperities (Lee et al. 2001; Liu et al. 2016). The non-associative Mohr-Coulomb criterion is adopted to characterize the sliding and dilatancy behaviors of bedding planes,

with the slip function F_J and the slip potential Q_J established on the asperity surface (Liu et al. 2016):

$$F_J(\sigma_n, \sigma_t) = |\sigma_n \sin \alpha + (\sigma_t - c^J) \cos \alpha| + \tan \varphi^J [\sigma_n \cos \alpha - (\sigma_t - c^J) \sin \alpha] \quad (14a)$$

$$Q_J(\sigma_t) = |\sigma_n \sin \alpha + \sigma_t \cos \alpha| \quad (14b)$$

where $\sigma_t = |T_t^J|$, $\sigma_n = T_n^J + b_0^J P$; φ^J and c^J are the basic frictional angle and cohesion of bedding planes. If the degradation process of surface roughness for bedding planes during shearing is considered, the equivalent asperity angle could be described as a function of plastic tangential energy (Liu et al. 2016).

2.3 Permeability variation model for layered rocks

The effective permeability of layered rocks is contributed by three parts, rock matrix, crack system and bedding planes. With the variation of crack system and deformation of bedding planes modeled with the constitutive model presented above, the permeability of deformable layered rocks changes accordingly. Following the two-step homogenization procedure, the effective permeability of layered rocks can be better express as (Liu et al. 2016)

$$K = (1 - \phi^c) k^s \delta + \frac{1}{4\pi} \int_{S^c} k_0^c \left(\frac{d}{d_0} \right)^{\chi-4/3} \frac{\beta^3}{\beta_0^3} (\delta - n' \otimes n') dS + k_0^J \left(1 + \frac{g_n^J}{a_0^J} \right)^3 \frac{a_0^J}{S^J} (\delta - n' \otimes n') \quad (15)$$

where k^s , k_0^c , k_0^J are the permeability of rock matrix, crack system with initial opening β_0 and density d_0 , and bedding plane with initial aperture a_0^J ; χ is an exponent representing cracks connectivity; ϕ^c is the volume fraction of cracks; g_n^J is the normal displacement jump of bedding plane. In Eq. (15), the change in the permeability of layered rocks under stress and pressure loading is caused by the damage growth of cracks (the 2nd term on the right hand side) and the deformation of bedding planes (the third term).

It can be seen from Eqs. (7), (8) and (15) that the evolution of strain, porosity and permeability of layered rocks under coupled HM loading condition are characterized with accounting the variation of multi-scale structures (cracks in smaller scale and bedding planes in much larger

scale). Both the initiation and propagation of cracks and friction sliding and dilatancy of bedding planes are well simulated by the proposed model. When only considering the coupled processes in rock blocks without accounting bedding planes, the coupled models presented in Eqs. (7), (8) and (15) can be simplify for the case of saturated cracked rocks as

$$E = S^c : (\Sigma + pB) + E^c \quad (16)$$

$$\phi - \phi_0 = B : S^c : (\Sigma + pB) + \delta : E^c + \frac{p}{N} \quad (17)$$

$$K = (1 - \phi^c) k^c \delta + \frac{1}{4\pi} \int_{\Omega} k_0^c \left(\frac{d}{d_0} \right)^{2/3} \frac{\beta^3}{\beta_0^2} (\delta - n^c \otimes n^c) dS \quad (18)$$

3. Computation approach and model validation

The proposed constitutive model presented in Eqs. (7)~ (9) and the effective permeability model presented in Eq. (15) for layered rocks have been integrated in previous developed finite element code (Liu et al. 2016), and then coupled with the well- established computer code, TOUGHREACT (Xu et al., 2011). Being widely used in practice, TOUGHREACT is capable of handling coupled hydraulic, thermal, chemical and biological processes in subsurface geological media with physical and chemical heterogeneity under non-isothermal, multiphase, multicomponent condition. TOUGHREACT had been linked with geomechanics codes to perform coupled thermal, hydrological, chemical and mechanical (THMC) simulations, such as TOUGHREACT-FLAC which links TOUGHREACT with FLAC3D (Itasca, 2009) and has been applied to analyze THMC processes in geologic radioactive waste repository (Zheng et al. 2015, 2017).

In this study, TOUGHREACT is used to solve the fluid flow problem and determine the fluid pressure distribution used for mechanical process analysis, the governing equations of fluid flow implemented in TOUGHREACT can be referred to Xu & Pruess (2001). Note that the fluid pressures modeled in TOUGHREACT are at the center point of each element, which should be interpolated to the corners of each element for mechanical process analysis. Due to the strongly nonlinearity of presented micromechanical damage constitutive model, the H-M-D coupled processes for layered rocks is appropriate to solved sequentially with an interlaced algorithm (Fig.

2). At each time step Δt , the fluid pressure p is first solved by the TOUGHREACT code, and then a prediction-correction algorithm is utilized for handling the mechanical-damage coupled process (Liu et al. 2016) and updating the permeability and porosity of layered rocks utilized in the TOUGHREACT.

Fig. 2 Schematic of ToughReact-based H-M-D coupled simulation for layered rocks

(1) Numerical simulation of laboratorial water injection test in rock blocks

The proposed model is first validated with the experimental data of hydraulic fracturing under water injection process on coal sample (Wu et al. 2018). During the experiment, water was continuously injected to the circular hole in the center of the cube coal sample after confining pressures being applied on the outer boundaries. Injection pressure and acoustic emission events were monitored with increasing of injection time. To simulate the experiment, the numerical model used in the simulation study is a square domain with side length of 0.3m and a circular hole with radius of 0.004m in the center. During the numerical simulation, the rock is assumed rigid with only the hydraulic fracture considered.

The finite element mesh used in simulation is shown in Fig. 3, which has 3200 elements and 6560 nodes. The left and bottom side are constrained with rollers, while the top and right boundary are applied with compressive stresses of 15MPa and 12 MPa, respectively. At initial state, the whole numerical calculation domain has a uniform water pressure of 0.1MPa. The injection rate of water into the center hole is 0.15mL/s. In consideration of the compressibility effects of the experimental system (Gao and Ghassemi 2020), a small injection rate of 0.0075mL/s is applied in the first 120s before water is injected from the center hole boundary at constant rate of 0.15mL/s. The parameters for modeling the hydraulic fracturing experiment are listed in Table 1,

the initial isotropic permeability of the experimental sample is $1 \times 10^{-17} \text{m}^2$ adopted from Yi et al. (2019), the Biot coefficient is 0.8 taken from Hu et al. (2010).

Fig. 3 Finite element mesh used in simulation of water injection test in rock block

Table 1 Model parameters for the hydraulic fracturing experiment

Parameter	Setting
Young's modulus of solid matrix E^s	4.0 GPa
Poisson's ratio of solid matrix ν^s	0.3
Critical damage resistance of microcrack $V(d_c)$	3×10^{-4} MPa
Critical damage d_c	1.0
Biot coefficient for rock block b_0^R	0.8
Initial opening of microcrack β_0	0.01
Initial crack density d_0	0.02
Isotropic permeability of rock matrix k^s	$1.0 \times 10^{-18} \text{m}^2$
Initial permeability of microcracks k_0^c	$1.4 \times 10^{-15} \text{m}^2$
Exponent constant χ	1.5
Time step Δt	30 s

Fig. 4 shows the computed and measured water injection pressure at point A (Fig. 3) near the center hole surface. The injection pressure increases sharply after a slow growth at the beginning with little frequency of acoustic emission hits. The model calculation match well with the experimental results. The calculated water injection pressure increases up to about 17MPa in the first 300s, at which time the sample begins to break, and then basically remains constant, and data from the test show similar behavior. Note that model and data have slight discrepancy as the data shows oscillation probably due to the heterogeneity of tested sample and model has simplification and uncertainties in material parameters. but the ballpark behavior is well reflected. A significant overestimation of data by the model without the mechanical process indicates the importance to consider the coupled hydraulic-mechanical processes and the effectiveness of the proposed model.

Fig. 4 Measured and predicted injection pressure varied with injected time

Fig. 5 shows the fracturing characteristics obtained by the experiment and distribution of damage-induced permeability variation at the end of numerical simulation. Under the water injection, the predicted damage-induced permeability increases up to 3 orders of magnitude. The macro hydraulic fractures generated in the experiment are discontinuous and stochastically propagated. While the damage zone predicted by the calculated damage-induced permeability change is expanded continuously in all directions around the hole and more developed in the maximum boundary stress direction, which is similar to the acoustic emission distribution. From the above analysis based on Figs. 4 and 5, one can find that although the proposed model in this study is insufficient to explicitly capture the macro discontinuous fracture developing pattern, it can reflect the ballpark of hydraulic fracturing response and is therefore feasible. The simulation results are expected to improve with a more accurate and comprehensive calibration of the model parameters.

Fig. 5 (a) Failure characteristics obtained by the hydraulic fracture test (Wu et al. 2018); (b) The

acoustic emission hit distributions during the test; (c) Distribution of damage induced permeability change by the proposed model at final injection time (unit: m^2)

(2) Numerical simulation of anisotropic strength tests on layered rocks

The anisotropic strength experimental data of Martinsburg slate (Donath et al. 1964) conducted under different foliation angles ($0^\circ \sim 90^\circ$) and confining pressures (3.5MPa $\sim$ 100MPa) is used to validate the approach (Eq. 13) for considering the mechanical interaction between cracks and bedding planes. The model parameters are the same as those (Liu et al. (2016)) used in the validation of the first approach (Eq. 12), except the parameters φ and V_0 in Eq. 13 used for

characterizing crack-bedding plane interaction are calibrated by fitting the test results: $\varphi=0.01$; V_0

increases linearly with confining pressure, $V_0 = 0.15869 + 0.00539 \times (-\sigma_3)$.

Fig. 6 plots the measured strengths of Martinsburg slate by experiment and predicted values by the proposed model incorporating the approach in Eq. 13 simulating crack-bedding plane interaction. With the increase of θ , the strength of Martinsburg slate decreases first ($\theta < 60^\circ$) and then increases ($\theta > 60^\circ$), displaying a typical “U-shaped” variation. The model predictions can capture the anisotropic strengths of Martinsburg slate under different foliation angles and confining pressures. The simulated results are in good agreement with the experimental data except for $\theta = 90^\circ$, the inconsistency at $\theta = 90^\circ$ would be improved by further accounting the influence of loading direction. Compared with the predictions (shown by dash-dot lines in Fig. 6) without considering crack-bedding plane interaction demonstrates that the approach in Eq. 13 can well represent this interaction for anisotropic strengths characterization. Fig. 7 shows the variation of the critical crack

damage resistance $V(d_c)$ with the angle between crack and bedding plane calculated by Eq. (13)

for simulating the test results under 50MPa confining pressure. The critical crack damage

resistance $V(d_c)$ increases with the augment of the angle between crack and bedding plane, it gets

the maximum value when the crack is perpendicular to the bedding plane and the minimum value

when the crack is parallel to the bedding plane.

Fig. 6 Measured (dot points) and predicted (solid lines) strengths of Martinsburg slate under different foliation angles and confining pressures.

Fig. 7 Variation of $V(d_c)$ predicted by Eq. (13) with the angle between crack and bedding plane

To evaluate the influences of parameters used for characterizing crack-bedding plane interaction, sensitivity studies on the parameters ϑ and V_0 are conducted at $-\sigma_3 = 50\text{MPa}$ by varying ϑ from 0.01 to 1.0 and V_0 from 0.2 to 1.2MPa. Fig. 8 shows the parameters ϑ and V_0 have important influences on the anisotropic strengths of layered rocks. With the increase of ϑ and V_0 , the compressive strength generally increases, except in the sliding mode of failure controlled by the sliding strength of the bedding plane. A higher value of ϑ results in a smaller difference of the

critical crack damage resistance between cracks parallel and perpendicular to the bedding plane.

With the increase of ϑ , the compressive strength in non-sliding failure mode (Liu et al. 2016)

generally increases. $\vartheta = 1.0$ represents the neglect of crack-bedding plane interaction, at this

situation the strength of layered rocks keeps constant in the non-sliding mode of failure ($\theta < 30^\circ$).

The crack damage resistance in different orientations is linearly dependent on the value of V_0 , with

the increase of V_0 the compressive strength gradually increases.

Fig. 8 Simulated Martinsburg slate strengths at 50MPa confining pressure with changes of (a) ϑ

and (b) V_0

4. A Numerical example at field scale

To further evaluate the effectiveness and accuracy of the proposed coupled H-M-D modeling approach, in this section numerical model was developed to simulate hydraulic fracturing at the field scale, focusing on exploring the effect of several key factors: injection rate, confining stress, and existing bedding planes on fracturing. The size of the computational model is 50m $\times$ 50m in cross-section and 1m in thickness, with 1681 elements and 3528 nodes, as shown in Fig. 9. The in-situ stresses are set to be 14MPa in horizontal direction and 10MPa in the vertical direction, with

uniform fluid pressure of 2MPa. Water injection with a constant rate of 0.4L/s is applied at the injection point in the center of the calculation area. The total injection time is set to be 8 minutes. Table 2 lists the computational parameters used in the simulation, the initial permeability of rock blocks, contributed by rock matrix and randomly-distributed cracks, is isotropic with value of $1 \times 10^{-15} \text{ m}^2$. Note that the computational parameters for bedding planes are only used in the cases with existing bedding planes, while in the other cases no bedding planes are accounted for. Since the practically damage density and damage-induced permeability would not increase limitlessly, the maximal damage is assumed to be two times bigger than the critical damage in the simulation.

Fig. 9 Computational domain and finite element mesh for water injection in field scale

Table 2 Computational parameters used for numerical examples

Category	Parameter	Setting
Rock block	Young's modulus of solid matrix E^s	10.0 GPa
	Poisson's ratio of solid matrix ν^s	0.3
	Critical damage resistance of microcrack $V(d_c)$	3×10^{-4} MPa
	Critical damage d_c	0.5
	Biot coefficient for rock block b_0^R	0.8
	Initial opening of microcrack β_0	0.01
	Initial crack density d_0	0.02
	Isotropic permeability of rock matrix k^s	$1.0 \times 10^{-16} \text{ m}^2$
	Initial permeability of microcracks k_0^c	$1.4 \times 10^{-13} \text{ m}^2$
	Exponent constant $\mathcal{K}$	1.9
Bedding plane	Initial aperture a_0^J	0.02mm
	Average spacing S^J	0.1 m
	Initial permeability of bedding plane k_0^J	$5.0 \times 10^{-12} \text{ m}^2$
	Normal stiffness H_T	200 MPa/mm
	Tangential stiffness H_N	200 MPa/mm

Biot coefficient for bedding plane b_0^J	1.0
--	-----

Numerical simulations are firstly conducted with three different time steps: 20s, 30s and 40s, to verify the numerical stability. Fig. 10 plots the calculated evolution of pressure at the central injection point with different time steps. The pressures at the injection point with different time

steps are very close. Fig. 11 depicts the distributions of mean damage density $\bar{d} = \frac{1}{4\pi} \oint_S d dS$ at the final injection time (480s) for three different time steps. One observes that the damage distribution results for the three cases are almost the same. The agreements of pressure and damage results obtained with different time steps demonstrate the stability of the proposed model.

Fig. 10 Evolution of the pressure at central injection point with different time steps

Fig. 11 Distribution contours of mean damage density $\bar{d}$ at final injection time for three different time steps

4.1 The effect of injection rate

Three constant injection rates, 0.2L/s, 0.4L/s, and 0.6L/s, are adopted in this part to study the

influence of injection rate on the pressure and damage evolution processes by the proposed model. Fig. 12 displays the evolution of injected pressure at the central injection point with the three injected rates. The bigger the injection rate, the larger the calculated injection pressure. Under each of the three injected rates, the injection pressure increases greatly at the beginning of injection, and then tends to be stable gradually. At the final injection time, 480s, the water pressure at the central injection point is 20.1MPa, 23.8MPa, and 27.1MPa corresponding to injection rates of 0.2L/s, 0.4L/s, and 0.6L/s, respectively.

Fig.12 Evolution of the pressure at central injection point with different injection rates

The distribution contours of damage densities at different times for the cases of different injection rates are shown in Fig. 13. The injection rate plays an important role in the damage distribution. The size of the damage area with mean damage density larger than two times of the initial value increases with the rise of the injection rate. The injection induced damage propagates around the injection point. The closer to the injection point, the more severely the damage develops. With the growth of injection time, the damaged area expands in all directions. Due to the anisotropy of in-situ stresses, the shape of the damaged area is elliptically distributed in space, with larger length developed in the X direction (applied with larger in-situ stress). Water injection induced damage propagation in the direction parallel to greater in-situ stress requires smaller fluid pressure. Since reservoir production usually enhances under larger damage areas in underground resource exploitation projects, it's better to adopt a larger injection flow in practice under the allowance of

operation equipment capacity.

(a) Injection rate of 0.2L/s

(b) Injection rate of 0.4L/s

(c) Injection rate of 0.6L/s

Fig. 13 Distribution contours of mean damage density $\bar{d}$ with the injection rate of (a) 0.2L/s, (b) 0.4L/s and (c) 0.6L/s

Figs. 14-16 display the variation of the calculated water pressures and damage densities along the profiles P_h and P_v (see Fig. 9 for their alignments) at different times under three different injection rates. Along the two profiles, the damage density and elevated pressure both decrease rapidly with the increase in the distance from the injection point. The larger the injection rate, the bigger the damaged area and elevated pressure region at same injection time. Under the same injection rates, the damage density and elevated pressure along profiles P_h and P_v increase with injection time. The

greater the damage area, the larger the elevated pressure region. The elevated pressure region is larger than the damaged area, demonstrating the water pressure enhancement effect caused by water injection also extends to the undamaged area. At final injection time, the distance of undamaged area from the injection point is 5.2m and 2.9m along profile P_h and P_v respectively under 0.2L/s injection rate case, increases to 6.3m and 4.3m under 0.4L/s injection rate case, 7.6m and 5.2m under 0.6L/s injection rate case. The injection-induced damage area, more developed along profile P_h , expands obviously with increasing of injection rate.

Fig. 14 Variation of the calculated damage density and water pressure along the profiles (a) P_h and (b) P_v under injection rate of 0.2L/s

Fig. 15 Variation of the calculated damage density and water pressure along the profiles (a) P_h and (b) P_v under injection rate of 0.4L/s

Fig. 16 Variation of the calculated damage density and water pressure along the profiles (a) P_h and (b) P_v under injection rate of 0.6L/s

4.2 The effect of in-situ stress

The influence of in-situ stress on the hydraulic fracturing processes is further analyzed in this subsection by varying the vertical in-situ stress at injection rate of 0.4L/s. Two cases with vertical in-situ stress of 14MPa and 18MPa are studied, while the horizontal in-situ stress keeps constant value of 14MPa. The variation of injected pressure at injection point under different in-situ stress are calculated and depicted in Fig. 17. With the increasement of vertical in-situ stress, the calculated injection pressure increases. The simulated final injection water pressure at injection point enhances from 23.8MPa to 28.2MPa as the vertical in-situ stress increases from 10MPa to 18MPa.

Fig. 17 Evolution of the pressure at central injection point with different in-situ stresses

Figs. 18 and 19 shows the distributions contours of damage and pressure at final injection time with different vertical in-situ stresses. For different cases of in-situ stresses, the shape of elevated pressure region is similar to the damaged area. In the 14MPa vertical in-situ stress case, that is

isotropic stress state, the damage extends almost uniformly in all directions, the elevated pressure and damage contours are approximately in circular shape. But, in the 18MPa vertical in-situ stress case, the elevated pressure and damage areas extend preferentially in the vertical direction, which is contrary to that of 10MPa vertical in-situ stress case. The size of damage area generally decreases with the increase of in-situ stress level, resulting from the expected constraint effect of damage propagation with increase of confining stresses. The anisotropy of in-situ stresses affects the anisotropic distribution characteristics of damage and pressure.

Fig.18 Distribution contours of damage at final injection time with different vertical in-situ stresses

Fig.19 Distribution contours of pressure at final injection time with different vertical in-situ stresses

Variation of water pressures and damage densities along the profiles P_h and P_v (see Fig. 9 for their alignments) at final injection time with different in-situ stresses are displayed in Fig. 20. Along the profiles P_h , the size of damaged area decreases with the increase of vertical in-situ stresses, which is expected since the normal stresses are increased, damage propagation is more likely to be constrained. As a result, the elevated water pressure decreases more rapidly with the increase of distance from the injection point under higher vertical in-situ stresses. But along the profile P_v , due to the state of constant horizontal stress the damaged areas under different cases are relatively

close. The variation characteristics of water pressure and damage in the calculated domain are influenced by the in-situ stress level, determined by the geological condition.

Fig. 20 Variation of damage and water pressure along the profiles (a) P_h and (b) P_v at final injection time under different in-situ stresses

4.3 The effect of bedding planes

In the above simulations, bedding planes was not considered in the model. In this section, the effect of bedding planes on water injection and fracturing is investigated for the case with injection rate of 0.4L/s and in-situ stresses of $\sigma_x = 14\text{MPa}$, $\sigma_z = 10\text{MPa}$. The computational parameters for bedding plane are listed in Table 2. In initial state, the permeability of layered rocks in foliation direction contributed by bedding planes is $1.0 \times 10^{-15} \text{ m}^2$, equals to the initial permeability of rock blocks.

Fig. 21 shows the variation of injected pressure at injection point with accounting the influence of vertical bedding planes. The calculated injection pressure decreases with the existence of bedding planes. Under the same injection rate, the simulated final injection water pressure is 18.9MPa with existence of bedding planes, while is 23.8MPa in no bedding plane case. The case of no crack deformation, only consider the deformation of bedding plane, is also investigated in Fig. 21. Without consideration the change of cracks structure, the injection water pressure increases greatly with final injection pressure of 32.1MPa, demonstrating the importance to account crack propagation and deformation. Both the damage of cracks and deformation of bedding planes affect the water injection responses in layered rocks.

Fig. 21 Evolution of injection pressure at central injection point for layered rocks

The distributions contours of damage and pressure at final injection time with accounting vertical and horizontal bedding planes are depicted in Figs. 22 and 23. In the vertical bedding plane case, damage propagation is more developed in vertical direction, not along the direction applied with larger in-situ stress. In the horizontal bedding plane case, the length of damage propagation in the horizontal direction is longer than that of no bedding plane case (Fig.13b). The injection-induced damage area is highly influenced by the bedding planes. The distributions contour of elevated pressure in elliptic shape is also affected by the existence of bedding planes. The major axis of the elliptic elevated pressure region is in the same direction with the bedding plane. The injection-induced opening of bedding plane is closely related to the value of elevated pressure, the aperture contours of bedding plane has a similar shape to the elevated pressure region (Fig. 24). The larger the elevated pressure, the bigger the aperture of bedding plane.

Fig. 22 Distribution contours of damage at final injection time with different orientations of bedding planes

Fig. 23 Distribution contours of pressure at final injection time with different orientations of bedding planes

Fig. 24 Aperture contours of bedding plane at final injection time with different orientations of bedding planes (unit: mm)

Fig. 25 depicts the variation of water pressures and damage densities along the profiles P_h and P_v (see Fig. 9 for their alignments) at final injection time in consideration of bedding planes. It can be seen from Fig. 25 that the calculated damage and elevated pressure are affected by the orientation of bedding planes. In the vertical bedding plane case, the values of calculated damage density decrease rapidly with the distance from the injection point along both profiles P_h and P_v . The length of damage propagation is relatively small, 1.8m along profile P_h and 4.3m along profile P_v . The elevated pressure dissipates quickly along profile P_h , but slowly along profile P_v due to the influence of vertical bedding plane. In the horizontal bedding plane case, injection-induced damage propagation is much more developed along profile P_h (with the length of 9.0m) than that along profile P_v (with the length of 2.2m). The elevated pressure region is also more expanded along profile P_h , the injected fluid tends to preferentially flow in the same direction with bedding plane. For the above analysis, one can find that the existence of bedding planes can facilitates damage propagation and preferential fluid flow along the direction of bedding planes.

Fig.25 Variation of damage and water pressure along the profiles (a) P_h and (b) P_v at final injection time with influences of bedding planes

The distribution contour of elevated pressure is closely related to the enhancement of permeability during injection process. Figs. 26 and 27 shows the injection-induced changes in permeability for layered rocks with vertical and horizontal bedding planes, in which K_x and K_z are the horizontal and vertical permeabilities, with superscripts J and R represent the contributions from bedding planes and rocks blocks. Although a weak permeability anisotropy of layered rocks is assigned in initial state (with the anisotropy ratio of 2), the injection-affected area has a strong permeability anisotropy at the final injection time due to the opening of oriented bedding planes. In the vertical bedding plane case, the horizontal permeability of layered rocks along profile P_h increases drastically up to two orders of magnitude (maximum value of $2.8 \times 10^{-13} \text{ m}^2$), and reduces rapidly towards its original magnitude ($1.0 \times 10^{-15} \text{ m}^2$) with the increase of distance from the injection point. The change of K_x along profile P_h is only controlled by the injection-induced damage in rock blocks. Along profile P_v , the change in vertical permeability of layered rocks is contributed by both the injection-induced damage in rock blocks and opening of bedding planes. The cracks damage-induced variation in K_z is dominant only within 0.35m away from the injection point, while the opening of bedding planes, results from the decrease of effective stress with increase of water pressure, contributes to enhancement of permeability in a much farther region.

In the horizontal bedding plane case, the permeability of layered rocks changes in a different pattern. The horizontal permeability K_x attains the maximum value of $3.2 \times 10^{-13} \text{ m}^2$ at the injection point. As the distance from the injection point increases, K_x first reduces rapidly within 0.6m, determined both by the damage of cracks and opening of bedding planes, and then slowly towards

the original value, determined mainly by the opening of bedding planes. Since the horizontal bedding planes pay no contribution to the vertical permeability of layered rocks, K_z along profile P_v is determined by the permeability of damaged rock blocks, which decreases sharply from the maximum value of $2.3 \times 10^{-13} \text{ m}^2$ to the initial permeability of $1.0 \times 10^{-15} \text{ m}^2$ within 1.6m away from the injection point.

From the above analysis, one can find that the variation pattern of K_z in the vertical bedding plane case and K_x in the horizontal bedding plane case are contributed by both the damage of cracks in smaller scales and deformation of bedding planes in larger scales, demonstrating the importance to consider the variation of multi-scale structures for better characterizing injection-induced permeability change in layered rocks. The existence of bedding planes and their orientation play a crucial influence on the water injection responses in underground layered rocks.

Fig. 26 Injection-induced permeability variation at final injection time along the profiles (a) P_h and (b) P_v for layered rocks with vertical bedding planes

Fig. 27 Injection-induced permeability variation along the profiles (a) P_h and (b) P_v for layered rocks

5. Conclusions

In this study, a coupled H-M-D modeling approach was developed for saturated layered rocks containing cracks in rock blocks separated by rough bedding planes based on a two-step homogenization. The free enthalpy of saturated layered rocks under coupled HM loading conditions is provided by characterizing the microcracking behavior of cracked rock blocks with the Eshelby solution-based micromechanical damage model and the deformation behavior of bedding plane with the elastoplastic model. The macroscopic stress–strain relation and porosity evolution equation are then obtained based on the free enthalpy in the framework of thermodynamics. In order to describe the anisotropic strength of layered rocks, the interaction between cracks and bedding planes is considered by two practical approaches which allow for studying the influences of bedding planes on the damage resistance of cracks. The permeability of layered rocks is also presented by the homogenization approach with the consideration of the contributions from cracks initiation and propagation in small scales and bedding planes opening and closing at larger scales, which are incorporated by the mechanical model. The key contribution of this study is that the proposed modeling approach simultaneously takes into account of the effect of multi-scale structures (cracks and bedding planes) variation on the deformation and permeability change in saturated layered rocks under coupled HM loading conditions.

The modeling approach was implemented into a well-established code TOUGHREACT, and validated with laboratory experiment of water injection test on coal sample. Good agreements were achieved between the computed injection pressures and the laboratory data: the key behavior, a drastic increase of water injection pressure (up to about 17MPa) in the first 300s that is followed by a pressure plateau was well captured by the model. Validation study performed with strength tests on Martinsburg slate demonstrated that the proposed model, which considers crack-bedding plane interaction, described well the typical “U-shaped” anisotropic strengths of layered rocks. The modeling approach was finally applied to study the effect of injection rate, confining stress, and existing bedding planes on the fluid injection responses in field scale. Under anisotropic *in situ* stresses condition, the elliptical shape of damage and elevated pressure was more developed in the direction with larger *in situ* stress, and as the injection rate increases, the size of damaged area and

elevated pressure region increase accordingly. While under isotropic *in situ* stress state the damage propagation and elevated pressure were approximately uniform in all directions. With the increase of *in situ* stress, the size of damage area generally decreased. When bedding planes were included in the model, in comparison with the case without bedding planes, the final injection pressure was lower; the distributions of damage and elevated pressure were more developed in the bedding plane direction. The size of damage propagation was larger in the direction of higher *in situ* stress for the case with the horizontal bedding plane whereas size of damage propagation was more developed in the direction of lower *in situ* stress for the case with vertical bedding plane case. The changes in the permeability of layered rocks during the injection process were caused by the damage propagation of cracks and opening of bedding planes. Compared with the contributions of bedding planes opening to the permeability change in layered rocks, the damage-induced permeability changes also play an important role and can't be ignored in the severely damaged area near the injection point. It is important to consider the variations of multi-scale structures for better modeling coupled HM processes in layered rocks.

Reference

- Barton, N., & Quadros, E. (2015). Anisotropy is everywhere, to see, to measure, and to model. *Rock Mechanics and Rock Engineering*, 48(4), 1323-1339.
- Cañamón, I., Ababou, R., Poutrel, A., & Udías, Á. (2019). Upscaling 3D coupled hydro mechanical properties of fractured porous rocks. *International Journal of Rock Mechanics and Mining Sciences*, 123, 104117.
- Chen, L., Shao, J. F., Zhu, Q. Z., & Duveau, G. (2012). Induced anisotropic damage and plasticity in initially anisotropic sedimentary rocks. *International Journal of Rock Mechanics and Mining Sciences*, 51, 13-23.
- Chen, Y., Zhou, C., & Sheng, Y. (2007). Formulation of strain-dependent hydraulic conductivity for a fractured rock mass. *International Journal of Rock Mechanics and Mining Sciences*, 44(7), 981-996.
- Chen, Y., Hu, R., Zhou, C., Jing, L. (2013). A permeability evolution model for crystalline rocks subjected to coupled thermo-hydro-mechanical loading. *Chinese Journal of Rock Mechanics*

- and Engineering, 32, 2185-2195. (In Chinese)
- Chen, Y. F., Wei, K., Liu, W., Hu, S. H., Hu, R., & Zhou, C. B. (2016). Experimental characterization and micromechanical modelling of anisotropic slates. *Rock Mechanics and Rock Engineering*, 49(9), 3541-3557.
- Cheng AH-D. Material coefficients of anisotropic poroelasticity. *Int J Rock Mech Min Sci.* 1997;34(2):199–205. [http://dx.doi.org/10.1016/S0148-9062\(96\)00055-1](http://dx.doi.org/10.1016/S0148-9062(96)00055-1).
- Donath FA. A strength variation and deformational behavior of anisotropic rocks. *State of stress in the earth's crust*. New York, NY: Elsevier; 1964; 281–297.
- Dormieux, L., Kondo, D., & Ulm, F. J. (2006). *Microporomechanics*. John Wiley & Sons.
- Figueiredo, B., Tsang, C. F., Rutqvist, J., Bensabat, J., & Niemi, A. (2015). Coupled hydro-mechanical processes and fault reactivation induced by CO₂ injection in a three-layer storage formation. *International Journal of Greenhouse Gas Control*, 39, 432-448.
- Forero, J. H., Gomes, G. J., Vargas Jr, E. A., Falcão, F. O., & Velloso, R. Q. (2020). A cross-anisotropic elastoplastic model applied to sedimentary rocks. *International Journal of Rock Mechanics and Mining Sciences*, 132, 104419.
- Gao, Q., & Ghassemi, A. (2020). Three dimensional finite element simulations of hydraulic fracture height growth in layered formations using a coupled hydro-mechanical model. *International Journal of Rock Mechanics and Mining Sciences*, 125, 104137.
- Guayacan-Carrillo, L. M., Ghabezloo, S., Sulem, J., Seyedi, D. M., & Armand, G. (2017). Effect of anisotropy and hydro-mechanical couplings on pore pressure evolution during tunnel excavation in low-permeability ground. *International Journal of Rock Mechanics and Mining Sciences*, 97, 1-14.
- Guo, L. L., Zhang, Y. B., Zhang, Y. J., Yu, Z. W., & Zhang, J. N. (2018). Experimental investigation of granite properties under different temperatures and pressures and numerical analysis of damage effect in enhanced geothermal system. *Renewable energy*, 126, 107-125.
- Heng, S., Yang, C. H., Guo, Y. T., Wang, C. Y., & Wang, L. (2015). Influence of bedding planes on hydraulic fracture propagation in shale formations. *Chinese Journal of Rock Mechanics and Engineering*, 34(2), 228-237. (In Chinese)
- Hu, C., Lemarchand, E., Dormieux, L., & Skoczylas, F. (2020). Quasi-isotropic Biot's Tensor for Anisotropic Porous Rocks: Experiments and Micromechanical Modelling. *Rock Mechanics*

and Rock Engineering, 1-11.

- Hu, D. W., Zhou, H., Zhang, F., & Shao, J. F. (2010). Evolution of poroelastic properties and permeability in damaged sandstone. *International Journal of Rock Mechanics and Mining Sciences*, 47(6), 962-973.
- Izadi, G., & Elsworth, D. (2014). Reservoir stimulation and induced seismicity: Roles of fluid pressure and thermal transients on reactivated fractured networks. *Geothermics*, 51, 368-379.
- Ismael, M., Konietzky, H., & Herbst, M. (2019). A new continuum-based constitutive model for the simulation of the inherent anisotropy of Opalinus clay. *Tunnelling and Underground Space Technology*, 93, 103106.
- Kim, J., Sonnenthal, E., & Rutqvist, J. (2015). A sequential implicit algorithm of chemo-thermo-poro-mechanics for fractured geothermal reservoirs. *Computers & Geosciences*, 76, 59-71.
- Lee, H. S., Park, Y. J., Cho, T. F., & You, K. H. (2001). Influence of asperity degradation on the mechanical behavior of rough rock joints under cyclic shear loading. *International Journal of Rock Mechanics and Mining Sciences*, 38(7), 967-980.
- Liu, W. (2018). Coupled damage and friction model for persistent fractured rocks considering multi-scale structures. *Chinese Journal of Geotechnical Engineering*, 40, 147-154. (In Chinese)
- Liu, W., Chen, Y. F., Hu, R., Zhou, W., & Zhou, C. B. (2016). A two-step homogenization-based permeability model for deformable fractured rocks with consideration of coupled damage and friction effects. *International Journal of Rock Mechanics and Mining Sciences*, 89, 212-226.
- Maghous, S., Dormieux, L., Kondo, D., & Shao, J. F. (2013). Micromechanics approach to poroelastic behavior of a jointed rock. *International Journal for Numerical and Analytical Methods in Geomechanics*, 37(2), 111-129.
- Qi, M., Shao, J. F., Giraud, A., Zhu, Q. Z., & Colliat, J. B. (2016). Damage and plastic friction in initially anisotropic quasi brittle materials. *International Journal of Plasticity*, 82, 260-282.
- Rutqvist, J., Rinaldi, A. P., Vilarrasa, V., & Cappa, F. (2019). Numerical Geomechanics Studies of Geological Carbon Storage (GCS). In *Science of Carbon Storage in Deep Saline Formations* (pp. 237-252). Elsevier.
- Taron, J., & Elsworth, D. (2009). Thermal–hydrologic–mechanical–chemical processes in the evolution of engineered geothermal reservoirs. *International Journal of Rock Mechanics and*

Mining Sciences, 46(5), 855-864.

- Wilkins, A., & Qu, Q. (2020). A formalism to compute permeability changes in anisotropic fractured rocks due to arbitrary deformations. *International Journal of Rock Mechanics and Mining Sciences*, 125, 104159.
- Wu, C., Zhang, X., Wang, M., Zhou, L., & Jiang, W. (2018). Physical simulation study on the hydraulic fracture propagation of coalbed methane well. *Journal of Applied Geophysics*, 150, 244-253.
- Wu, G., Chen, W., Rong, C., Jia, S., & Dai, Y. (2020). Elastoplastic damage evolution constitutive model of saturated rock with respect to volumetric strain in rock and its engineering application. *Tunnelling and Underground Space Technology*, 97, 103284.
- Xie, N., Zhu, Q. Z., Shao, J. F., & Xu, L. H. (2012). Micromechanical analysis of damage in saturated quasi brittle materials. *International Journal of Solids and Structures*, 49(6), 919-928.
- Xu, T., & Pruess, K. (2001). Modeling multiphase non-isothermal fluid flow and reactive geochemical transport in variably saturated fractured rocks: 1. Methodology. *American Journal of Science*, 301(1), 16-33.
- Xu, T., Sonnenthal, E., Spycher, N., & Pruess, K. (2006). TOUGHREACT—a simulation program for non-isothermal multiphase reactive geochemical transport in variably saturated geologic media: applications to geothermal injectivity and CO₂ geological sequestration. *Computers & geosciences*, 32(2), 145-165.
- Yi, L. P., Li, X. G., Yang, Z. Z., & Waisman, H. (2019). A fully coupled fluid flow and rock damage model for hydraulic fracture of porous media. *Journal of Petroleum Science and Engineering*, 178, 814-828.
- Zhang, Y., Hao, S., Yu, Z., Li, X., & Xu, T. (2018). Land uplift induced by injection: a feasible method to evaluate the security of CO₂ capture and sequestration projects. *Environmental Earth Sciences*, 77(13), 513.
- Zheng, L., Rutqvist, J., Birkholzer, J. T., & Liu, H. H. (2015). On the impact of temperatures up to 200 C in clay repositories with bentonite engineer barrier systems: A study with coupled thermal, hydrological, chemical, and mechanical modeling. *Engineering Geology*, 197, 278-295.

- Zheng, L., Rutqvist, J., Xu, H., & Birkholzer, J. T. (2017). Coupled THMC models for bentonite in an argillite repository for nuclear waste: Illitization and its effect on swelling stress under high temperature. *Engineering geology*, 230, 118-129.
- Zhu, Q., Kondo, D., Shao, J., & Pensee, V. (2008). Micromechanical modelling of anisotropic damage in brittle rocks and application. *International Journal of Rock Mechanics and Mining Sciences*, 45(4), 467-477.
- Zhu, Q.Z. (2016). Strength prediction of dry and saturated brittle rocks by unilateral damage-friction coupling analyses. *Computers and Geotechnics*, 73, 16-23.
- Zhu, Q., & Shao, J. (2017). Micromechanics of rock damage: Advances in the quasi-brittle field. *Journal of Rock Mechanics and Geotechnical Engineering*, 9(1), 29-40.