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AN OVERVIEW OF TOUGH-BASED GEOMECHANICS MODELS

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ABSTRACT

After the initial development of the first TOUGH-based geomechanics model 15 years ago based on linking TOUGH2 multiphase flow simulator to the FLAC3D geomechanics simulator, at least 15 additional TOUGH-based geomechanics models have appeared in the literature. This development has been fueled by a growing demand and interest for modeling coupled multiphase flow and geomechanical processes related to a number of geoengineering applications, such as in geologic CO_2 sequestration, enhanced geothermal systems, unconventional hydrocarbon production, and most recently, related to reservoir stimulation and injection-induced seismicity. This paper provides a brief overview of these TOUGH-based geomechanics models, focusing on some of the most frequently applied to a diverse set of problems associated with geomechanics and its couplings to hydraulic, thermal and chemical processes.

Keywords: TOUGH, modeling, fluid flow, geomechanics, THMC

1 INTRODUCTION

A growing demand and interest for modeling coupled multiphase flow and geomechanical processes has resulted in the development of a growing number of models that adds geomechanics to the existing multiphase flow capabilities of the TOUGH family codes. This development started with the development of the TOUGH-FLAC simulator to meet the need for analyzing the effect of geomechanics on multiphase fluid flow behavior and transport properties around nuclear waste emplacement tunnels at the previously proposed U.S. high-level nuclear repository site at Yucca Mountain, Nevada (Rutqvist et al., 2002; Rutqvist and Tsang, 2012). The TOUGH-FLAC simulator was developed as a pragmatic approach, linking the two existing codes, TOUGH2 and FLAC3D (Rutqvist et al., 2002). The TOUGH-FLAC simulator has since been adapted and applied for a wide range of geoscientific research and geoengineering applications, such as geologic CO_2 sequestration, enhanced geothermal systems, and gas production from hydrate bearing sediments (Rutqvist (2011) and references therein).

Following the first development of the TOUGH-FLAC simulator, a number TOUGH-based geomechanical models have been and are being developed. In fact, at least 15 additional TOUGH-based geomechanics models of various sophistications have appeared in the literature. This include simulators such as TOUGH+ROCMECH (Kim and Moridis, 2013), TOUGH-RDCA (Pan et al., 2014a), TOUGH-CSM (Winterfeld and Wu, 2015), TOUGH-RBSN (Kim et al., 2015a), and many more linking TOUGH-family codes, such as TOUH2, TOUGH-MP, TOUGH+, TOUGHREACT, and ITOUGH to various geomechanics models. For example, TOUGHREACT has been linked to geomechanics models for the analysis of coupled thermal, hydraulic, mechanical and chemical (THMC) processes (e.g., Taron et al., 2009; Zheng et al., 2014; Kim et al., 2015b). In recent years, additional interest and demand have been fueled by the need stimulate reservoirs through fracturing (e.g., for enhanced geothermal systems or tight gas and shale gas formations), understand the risk of leakage (e.g., at carbon storage sites), and to address the issue of induced seismicity.

This paper provides a brief overview of the current TOUGH-based geomechanics models, including capabilities, applications and potential future developments. Table 1 lists and briefly describes 20 TOUGH-based geomechanics models that have appeared in the literature. In general these TOUGH-based geomechanics models differ in the assumptions about the mechanical behavior of porous and fractured geologic media, the numerical method used to perform the stress–strain calculation, the discretization scheme and how state variables and parameters calculated for potentially different meshes are mapped to each other, and the way to couple fluid flow and geomechanics. Although the TOUGH-based geomechanics models are developed for modeling coupled thermal-hydraulic-mechanical (THM) processes or, in some cases, even THMC processes, the couplings of fluid flow and geomechanics, i.e., HM couplings, are central to most applications and are known to be challenging to solve numerically depending on the specific application. Therefore, an overview of numerical schemes related to HM couplings schemes is devoted to the entire next section. This is followed by descriptions of TOUGH-FLAC, TOUGH-ROCMECH, TOUGH-RDCA, TOUGH-CSM, and TOUGH-RBSN, which are complementary TOUGH-based geomechanical models that have been most frequently applied to a diverse range of problems. Thereafter, other TOUGH-based geomechanics models listed in Table 1 are briefly reviewed before concluding the paper with some final thoughts on the current state of TOUGH-based geomechanics models expected future developments.

2 HM COUPLING SCHEMES

Figure 1 shows a schematic of the couplings between hydraulic and mechanical processes in a deformable porous media such as soil and rock (Rutqvist and Stephansson, 2003). The arrows indicate the couplings, which can be divided into two categories: direct (solid line arrows) and indirect (dashed line arrows). Direct couplings are associated with pore-volume changes and their instantaneous and direct effect on fluid mass balance and effective stress, whereas indirect couplings are occurring indirectly through changes in mechanical and hydraulic properties.

Depending on the type of problem being solved and the porous medium properties, the importance of different HM couplings varies. In relatively permeable fractured hard rock, the indirect coupling in the form of permeability changes with stress might be most important. In relatively impermeable, soft and porous clay, on the other hand, direct pore-volume coupling may be most important. For example, when a porous deformable medium is suddenly loaded mechanically, the pores will be compressed and thereby squeezing the pore fluid to a higher pore pressure that will impact the fluid mass balance. This increase in pore-fluid pressure will in turn have an instantaneous effect on effective stress and volumetric strain. These are instantaneous two-way couplings between hydraulic and mechanical processes that can be challenging to resolve numerically.

A number of numerical schemes have been employed for solving coupled fluid flow and geomechanics problems (Minkoff et al., 2003; Kim, 2010). These include so-called fully coupled (monolithic) and sequentially coupled solution methods. In monolithic solutions, all the equations for fluid flow and mechanics including coupling terms are assembled into a large matrix system and solved simultaneously. Most of the coupled fluid flow and geomechanics finite element codes developed in rock and soil mechanics since the 1980s have employed fully coupled numerical schemes (e.g., Noorishad et al., 1982). The fully coupled method usually provides unconditional and convergent numerical solutions for mathematically well-posed problems (Noorishad et al., 1982; Rutqvist and Stephansson, 2003; Kim, 2010).

When linking two different codes for fluid flow and geomechanics, it is generally not possible to use the monolithic solution scheme. Consequently, in most TOUGH-based geomechanics models to date, including TOUGH-FLAC, the equations for fluid flow and geomechanics are solved sequentially. Sequential coupling methods might be prone to numerical instability and inaccuracy when solving problems involving strong direct pore-volume coupling. Analysis of sequential methods associated with pore-elasticity with appropriate stability properties has been the subject many studies (Settari and Mourits, 1998; Mainguy and Longueare, 2002; Kim et al., 2009). However, as shown by Kim (2010), by choosing an appropriate coupling scheme with so-called stress fixed iterations in the sequential scheme, the sequential solution becomes unconditionally stable. In a stress fixed sequential solution, flow is solved first, fixing the total stress field, and then geomechanics is solved from the variables obtained at the previous flow step. The stress fixed sequential scheme is achieved in the computation by calculating an appropriate porosity correction term while keeping the pore-compressibility non-zero and active in the reservoir simulator (Kim et al., 2011). Though the efficiency of the sequential, iterative schemes has been questioned (Prevost, 2013), a recent study showed that fixed stress split is a robust and efficient scheme for iteratively coupling poro-elastic systems even for highly nonlinear problems (Mikelíc et al., 2014).

For practical reasons, the sequential coupling method is used in all TOUGH-based geomechanics models except in some one-way coupled approaches and in TOUGH-CSM in which a monolithic solution is employed (Winterfeld and Wu, 2015). For strong pore-volume coupling, the various TOUGH-based geomechanics models, including TOUGH-FLAC, TOUGH+ROCMECH and TOUGH-CSM, have been verified against analytical solutions involving poro-elasticity such as solutions involving one-dimensional consolidation (Terzaghi) and the 2D Mandel-Cryer effects. These verifications have shown good agreement between numerical results and analytical solutions for both the fully coupled scheme in TOUGH-CSM (Winterfield and Wu, 2015) and sequentially coupled schemes in TOUGH+FLAC (e.g., Kim et al., 2012) and TOUGH+ROCMECH (e.g., Kim and Moridis, 2013). This shows that both monolithic and sequential coupling schemes can be used to solve problems involving strong pore-volume coupling, though the efficiency of the two schemes might be substantially different depending on the specific problem being solved.

In the development of coupled HM numerical models, a lot of effort is usually dedicated to verification of algorithms related to pore-volume coupling, partly because poro-elastic analytical solutions for such problems exist. However, in much of the multiphase flow applications encountered, direct two-way pore-volume couplings may not be important, or can be ignored by choosing an appropriate pore-compressibility in the flow simulator. More common is that indirect couplings by property changes dominate. Moreover, in many cases one-way coupling is sufficient, for example hydraulic-to-mechanical coupling considering how fluid pressure gives rise to mechanical deformation and failure. In other applications, such as fluid-driven hydraulic fracturing propagation, very strong pore-volume coupling appears, especially when new fracture volume is created at the crack tip, which is very challenging numerically, regardless of the applied HM coupling scheme.

3 TOUGH-FLAC

The TOUGH-FLAC simulator was originally developed in the late 1990s as part of the Yucca Mountain nuclear waste disposal project (Rutqvist et al., 2002; Rutqvist and Tsang, 2003a). At that time TOUGH2 (Pruess et al., 2012) was the main code used for the analysis of unsaturated zone flow and transport of the Yucca Mountain site, but there was a need to analyze how flow and transport was affected by geomechanical processes (Rutqvist and Tsang, 2003b). The idea was then to link TOUGH2 to a geomechanics code; the FLAC3D code (Itasca, 2012) was selected, because it had the required geomechanics capabilities, was a continuum code compatible with the TOUGH2 continuum approach, and was already qualified and applied in the Yucca Mountain Project (Rutqvist and Tsang, 2012).

While FLAC3D (Itasca, 2012) is a commercial code and the source code is not distributed, it contains a script programming capability called FISH, which makes it possible to reach and modify internal variables and thereby enabled the linking with the TOUGH2 code. FLAC3D also has the capability of implementing user defined constitutive models through C++

programing added in a dynamic link library file (Rutqvist, 2011). Thus, despite not having access to the source code, FLAC3D provides sufficient flexibility for research applications and specialized developments to a wide range of applications. In addition, FLAC3D contains a large number of constitutive models, including elasto-plastic and visco-elastic (creep) models for solids as well as the possibility of including some discontinuities as interfaces between solid elements.

As described in the previous section, TOUGH-FLAC uses sequential coupling between TOUGH2 and FLAC3D, whereby fluid flow variables, such as pore pressure, temperature, and saturation calculated by TOUGH2, are transferred to a compatible numerical grid for FLAC3D, which then calculates effective stresses and associated deformations, returning updated values for porosity, permeability, and capillary strength parameter to the flow simulator (Rutqvist et al., 2002; Rutqvist, 2011). As described in a 2011 status paper on TOUGH-FLAC (Rutqvist. 2011), TOUGH-FLAC was expanded to applications, including geomechanical aspects of CO_2 sequestration and fault activation, geomechanical effects in gas production from hydrate bearing sediments, and geothermal energy production. Since 2011, TOUGH-FLAC applications have been further broadened along with an increasing number of users, including continued modeling of geomechanical aspects of CO_2 sequestration (Cappa and Rutqvist, 2012; Mazzoldi et al., 2012; Rinaldi and Rutqvist, 2013; Jeanne et al., 2014a; Konstantinovskaya et al., 2014; Rinaldi et al., 2014a, b, 2015a; Figueiredo et al., 2015), nuclear waste disposal (Rutqvist et al., 2013; 2014), enhanced geothermal systems (Jeanne et al., 2014b-d, 2015a, b; Rutqvist et al., 2015a; Rinaldi et al., 2015b), underground gas storage and compressed air energy storage (Rutqvist et al., 2012a; Kim et al., 2013; Walsh et al., 2015), and gas production from hydrate bearing formations (Kim et al., 2012; Rutqvist et al., 2012a).

In the recent few years significant advancements of TOUGH-FLAC have been made, extending the simulations to more complex geomechanical processes, especially related to modeling injection-induced fault activation and induced seismicity (Rutqvist et al., 2014a; Rinaldi et al., 2015a), advanced constitutive models for expansive clay in nuclear waste isolation (Rutqvist et al., 2014b; Vilarrasa et al., 2015), and modeling of salt geomechanical processes coupled with temperature and multiphase flow (Blanco-Martín et al., 2015a; 2016). Fault activation and induced seismicity have been modeled in 3D using strain-softening (slip-weakening) fault friction models that enable modeling of sudden seismic slip (Rinaldi et al., 2015a). This includes recent 3D modeling of injection-induced fault activations associated with both underground CO_2 injection and during stimulation of shale-gas reservoirs (Rutqvist et al., 2015b; Rinaldi et al., 2015a). In some cases this has involved fully dynamic calculations of the fault activation and resulting ground surface motion (Rutqvist et al., 2014a). Implementation of more advanced fault frictional laws is underway; Urpi et al. (2016) present a first step in the implementation of a rate-and-state fault friction law into the TOUGH-FLAC framework.

The recent extension of the TOUGH-FLAC simulator for modeling THM processes associated with nuclear waste disposal in salt has been accomplished through collaboration between LBNL and Clausthal Technical University, Germany (Blanco-Martín et al., 2015b). This includes the development, implementation and application of an advanced constitutive model from Clausthal Technical University (the Lux/Wolters constitutive model) for THM induced damage, healing and sealing of salt host rocks and compaction of crushed salt

(Blanco-Martín et al., 2016). Moreover, this involves modeling of large strain along with the compaction of the crushed salt backfill from a porosity of about 30% to less than 1% (Blanco-Martín et al., 2015a, b). Clausthal Technical University uses a different coupling scheme in which FLAC3D is the main code driving the simulation forward, and denotes this simulator FLAC-TOUGH rather than TOUGH-FLAC (Lux et al., 2014; Blanco-Martín et al., 2015b).

Related to THM in clay, the implementation of the Barcelona Basic Model for mechanical behavior of unsaturated soils (Rutqvist et al., 2014b), and the Barcelona Expansive Model (Vilarrasa et al., 2015) for mechanical behavior of expansive soils are important additions for rigorous modeling of bentonite based backfill material. Moreover, the consideration of two structural levels, i.e., macro- and micro-structures in the expansive model, provides a link between mechanics and chemistry for more mechanistic modeling of THMC behavior. Two recent papers by Zheng et al. (2014; 2015) describe different types of chemical-mechanical coupling behavior in bentonite, i.e., effects of chemistry on the mechanical evolution of the bentonite material. In this case TOUGHREACT is linked to FLAC3D to model CM couplings, such as salinity effects on swelling pressure. Such chemical-mechanical coupling effects might be especially important when considering higher temperature disposal systems (Zheng et al., 2015).

Most recently, the TOUGH-FLAC approach has been extended and applied in inverse modeling, by linking FLAC3D to the ITOUGH simulation–optimization code (Finsterle, 2015) using the general structure of the TOUGH-FLAC simulator (Blanco-Martín et al., 2015c). The resulting simulator, ITOUGH-FLAC, provides an inverse modeling framework for the estimation of flow parameters, considering the system response accounting for geomechanical processes. Moreover, using iTOUGH2-PEST (Finsterle and Zhang, 2011) and

TOUGH-FLAC, both flow and mechanical parameters can be estimated, including sensitivity analysis, uncertainty propagation and data-worth analysis. Currently, iTOUGH2-PEST with TOUGH-FLAC has been applied for material parameter estimation by analyzing field data at the In Salah CO_2 storage project. Algeria (Rinaldi et al., 2015c), and at a multi-year in situ heating experiment at Asse mine in Germany (Blanco-Martín et al., 2016).

FLAC3D is a well-established code with a large user base (Itasca, 2012). It makes available many geomechanical constitutive models and has the flexibility to extend and implement new constitutive models, which is one of the most appealing features for selecting FLAC3D as the geomechanics code to be linked to TOUGH. One drawback with the current TOUGH-FLAC simulator is that it runs exclusively under Windows (because FLAC3D only runs under Windows), which prohibits the use ultra-large computer clusters. However, there are plans to port FLAC3D to Linux and to develop an MPI version in the near future (personal communication with Itasca, April 2016).

4 TOUGH-ROCMECH

TOUGH-ROCMECH is developed as an alternative to TOUGH-FLAC, in which the source code of the geomechanics part is available and therefore enabling a more efficient linking between multiphase flow and geomechanics, and the possibility of porting the simulator for computer clusters and massive parallel processing (Kim and Moridis, 2013). ROCMECH is an LBNL in-house developed finite element code that was tailored first for linking with TOUGH+ (Kim and Moridis, 2013) and later with TOUGHREACT (Kim et al., 2015b) and iTOUGH2 (Finsterle, 2015). Similar to TOUGH-FLAC, TOUGH-ROCMECH employs sequential coupling schemes, including the fixed stress split algorithms, which have been implemented and verified by Kim and Moridis (2013).

The current basic ROCMECH version has the capability of modeling mechanical failure within solid elements through elasto-plastic Drucker-Prager or Mohr-Coulomb models. This has recently been extended to consider failure on multiple shear planes representing fracture sets of different orientation and applied for the analysis of shear stimulation related to an enhanced geothermal project at the Newberry Volcano, Oregon (Smith et al., 2015). A new multiporosity approach for poro-elasticity was also developed and implemented by Kim et al. (2012). This version of TOUGHREACT-ROCMECH has also been applied for modeling THMC processes for flow along fractures, considering mechanical and chemical (precipitation) effects on porosity and permeability (Kim et al., 2015b). These are processes important for the long-term sustainability of enhanced geothermal systems and for sealing of fractures associated with geologic containment of CO_2 and nuclear waste disposal.

In a version of TOUGH+ROCMECH, capabilities for modeling 3D fracture propagation along a vertical pre-defined plane have been implemented. This model was applied for the analysis of hydraulic fracture propagation associated with stimulation of shale-gas reservoirs (Kim and Moridis, 2013; 2015). The approach is similar to that of Ji et al. (2009), in which the fracture propagates along the boundary of the model domain through a nodal-splitting algorithm. The permeability of fractured elements are increased with fracturing opening according to the cubic relation between flow and fracture aperture (Rutqvist and Stephansson, 2003). Using such an approach in the case of modeling hydraulic fracturing in tight shale, the

TOUGH+RealGasH2O with ROCMECH has been applied (Kim and Moridis, 2013; 2015). The vertical fracturing is modeled by adding traction boundary conditions at locations where nodes have been split. Moreover, once a fracture has been created adjacent to the solid element, the initial single continuum element in TOUGH is changed to multiple continuum for considering the local leak-off from the fracture to the surrounding porous rock.

In ROCMECH, fracturing conditions for node-splitting are based on tensile strength rather than toughness. A fracturing criterion considering the effects of both effective stress normal to the fracture and shear stress enables a mix-mode fracturing criterion. Using this model, Kim and Moridis (2015) were able to model multiphase flow driven hydraulic fracturing and found significant effects of complex two-phase flow processes, including vertical gravity segregation that are processes important for estimating the fracture volume and leak-off to the surrounding rock.

Ongoing developments of TOUGH-based geomechanics models linked to ROCMECH includes MPI versions of both TOUGH+ROCMECH and TOUGHREACT-ROCMECH, which will enable simulations of much larger problems using massive parallel processing on large scale computer clusters.

5 TOUGH-RDCA

Pan et al. (2014a) coupled TOUGH2 to RDCA (rock discontinuous cellular automaton), a code capable of simulating nonlinear and discontinuous deformation behavior, such as plastic yielding and the initiation, propagation and coalescence of cracks induced by changes of fluid pressure and temperature.

RDCA uses a special displacement function to represent internal discontinuities (Pan et al., 2014b). A level-set method tracks the fracturing path, and a partition of unity method is used to improve the integral precision of fracture surface and fracture tip calculations. The mechanical state is evaluated by a cellular automaton updating rule. In this approach, the discontinuity of a crack is incorporated independently of the mesh, such that the crack can be arbitrarily located within an element, i.e., the method does not require any re-meshing for crack growth. As a result, a fixed mesh can be used in RDCA and this greatly simplifies the modeling procedure and its sequential integration with TOUGH2. If a fracture propagates through a certain element, the permeability of this element is increased according to the cubic law with the additional permeability of the fracture superimposed on the initial permeability representing the rock matrix.

In TOUGH-RDCA, the fracturing condition can be evaluated either by linear elastic fracture mechanics using fracture toughness or by a modified Mohr-Coulomb criterion. The toughness-based criterion includes mixed Mode I (extension) and Mode II (shear) fracture propagation, whereas the Mohr–Coulomb criterion is modified with a tension cut-off, enabling modeling of both shear and tensile failure.

TOUGH-RDCA has been verified against analytical solutions and against TOUGH-FLAC for poro-elastic behavior and injection-induced ground surface uplift (Pan et al., 2013). A number of simulation applications have been presented related to fluid driven fracture propagation and CO_2 leakage through fractures. This includes multiple fracture propagation with intersections to pre-existing fractures (Pan et al., 2014c). The code is currently limited to modeling fracture propagation in 2D, whereas a 3D RDCA code is under development.

6 TOUGH-CSM

TOUGH-CSM is being developed at the Colorado School of Mines (CSM), with the ultimate goal of an efficient code tailored for massive parallel processing simulations (Winterfeld and Wu, 2012; 2015). The geomechanics part is accomplished by adding a mean stress equation for thermo-poroelastic multi-porosity media to the standard set of governing multiphase flow equations of TOUGH2-MP. In this formulation, the mean total stress is included as an additional primary variable, and the coupled thermal–hydrological–mechanical system is solved fully implicitly, obtaining volumetric strain and associated changes in porosity and permeability. Geochemical reactions based on the TOUGHREACT code have also been included in this formulation (Zhang et al., 2012; Winterfeld and Wu, 2012).

A few applications of TOUGH-CSM related CO_2 sequestration in deep sedimentary formations and geothermal systems have been published (Hu et al., 2013; Winterfeld and Wu, 2014). In the case of CO_2 sequestration, the effect of fracturing through the caprock overlying a reservoir was studied in Huang et al. (2015). Since only the mean stress was solved in the fully coupled simulation, some other relationships and assumptions were used to estimate the horizontal stress needed for evaluating the possibility of vertical fracturing through the caprock. The application example related to geothermal, using a version of the code denoted TOUGH-EGS, included simulation of ground subsidence at the Geyser geothermal field with comparison to the previous results obtained with TOUGH-FLAC (Hu et al., 2015).

As concluded in Hu et al. (2015), calculations limited to mean total stress as opposed to the full stress tensor is a simplification that may be a shortcoming since it cannot analyze phenomena dependent on shear stress, such as rock failure. However, currently a new algorithm is being developed and tested in which the stress tensor, including all normal and shear stress components, are solved in a sequential manner (Winterfeld and Wu, 2015). This approach of calculating the stress components was verified against analytical solutions showing the potential of TOUGH-CSM for realistic and efficient modeling coupled geomechanical processes using massive parallel processing.

7 TOUGH-RBSN

TOUGH-RBSN is being developed at LBNL with the main goal of modeling mass transport through permeable media under dynamically changing hydrologic and mechanical conditions in 3D heterogeneous geological media (Asahina et al., 2014; Kim et al., 2015a). A strong motivator is the potential of modeling discrete fracture propagation through heterogeneous geological media in 3D (Kim et al., 2015a). The simulation tool combines TOUGH2 with the rigid-body-spring network (RBSN) model, which enables a discrete (lattice) representation of elasticity, individual fractures and fracture networks in rock.

One advantage of linking TOUGH2 and RBSN resides in their common utilization of a set of nodal points and properties of the corresponding Voronoi tessellation (e.g., natural neighbor and volume rendering definitions). Shared use of the Voronoi tessellation facilitates every stage of the analyses, including model construction and results interpretation. In such a system, the discrete fractures are directly mapped onto unstructured Voronoi grids via an automated geometric scheme (Asahina et al., 2011). A fracture is represented by the controlled breakage of the springs (1D lattice elements) linking adjacent Voronoi cells along the fracture trajectory. Fractures can propagate along Voronoi cell boundaries as THM-induced stresses evolve and exceed prescribed material strength values. The fracturing process is represented by the damage/breakage of the springs. A Mohr-Coulomb criterion with tension cut-off is used to judge when a lattice element undergoes a fracturing event.

The RBSN code has been extensively used and validated for fracturing in concrete materials, including heterogeneities such as large grain inclusions, whereas the linked TOUGH-RBSN code has been verified against analytical solutions and other numerical tools for various features, including poro-elasticity, swelling, and fracture deformation (Asahina et al., 2014; Kim et al., 2015a). Applications include validation against experimental results on desiccation cracking in a fine-grained sediment (mining waste), and most recently modeling of fracture propagation through a heterogeneous laboratory sample that includes pre-existing weaknesses (Kim et al., 2015a).

Currently a new dynamic simulation framework for RBNS is being developed. In the new methodology, nodal kinematic information (displacements, velocities, and accelerations) is calculated through the explicit time integration scheme, by which the code implementation with parallelization can be easily realized. The parallelization will be a requirement for being able to solve large-scale problems in 3D with this approach.

8 OTHER TOUGH-BASED GEOMECHANICS MODELS

In addition to TOUGH-FLAC, TOUGH-ROCMECH, TOUGH-CSM, TOUGH-RDCA, and TOUGH-RBSN, a number of other TOUGH-based geomechanics models have been developed as listed in Table 1, though most of them have not been extensively applied.

Some of the earlier work includes Gosavi and Swenson (2005) who linked TOUGH2 to the finite element code GeoCrack3D, and later applied it to geothermal energy applications. Hurwitz et al. (2007) linked TOUGH2 to the USGS coupled hydro-mechanical finite element code Biot2, named the simulator TOUGH2-Biot, and applied it to study hydro-thermal fluid flow and deformation in large calderas. Recently another simulator named TOUGH2Biot was presented (Lei et al., 2015) involving TOUGH2 linked to an in-house finite element code and verified against previous TOUGH-FLAC simulations of the Geysers geothermal system and applied to simulate CO_2 injection of a site in China.

Taron et al. (2009) at Penn State University linked TOUGHREACT to FLAC3D, a TOUGH-based geomechanics model that has been applied for modeling THMC processes associated with geothermal systems (Taron et al., 2009; Taron and Elseworth, 2009; Izada and Elsworth, 2015). For example, Taron and Elseworth (2009) used THMC modeling to study the evolution of permeability associated with mechanical, thermal, and chemical (precipitation and dissolution) effects. In Izada and Elsworth (2014; 2015), the FLAC domain was populated with an implicit fracture network for the analysis of injection-induced micro-seismicity during hydraulic stimulation.

Other efforts includes Rohmer and Seyedi (2010) who linked TOUGH2 to the French open source finite element mechanics code Code_Aster and simulated deep underground CO_2 injection. Loschetter et al. (2012) used the TOUGH2-Code_Aster combination to model enhanced coalbed methane production. Aoyagi et al. (2013) linked TOUGH2 to FrontISRM, an open source finite element code in Japan, based on TOUGH-FLAC links, and demonstrated it by modeling a generic CO_2 injection simulation.

Some of the most recent efforts include Lee at al. (2015) who linked TOUGH2 to UDEC, which is a distinct element code, enabling modeling the geomechanical behavior of fracture networks in 2D. Miah et al. (2015) presented on-going work on linking TOUGH2 with PyLith, which is a USGS-developed finite-element code primarily used for large-scale geomechanical crustal deformation and earthquake simulation (static, quasi-static and dynamic modes). PyLith has advanced fault frictional models that will be applied and benchmarked against TOUGH-FLAC implementations of rate-and-state frictional models.

Finally, simpler TOUGH-based geomechanics approaches have been developed for specialized applications, including Walsh et al. (2012) who added the effects of an external, vertical stress change to the porosity updates. This approach was recently applied to model effects of glaciation in the safety assessment of a hypothetical nuclear waste repository (Calder et al., 2015). Another example is TOUGH2-Seed, a coupled fluid flow and mechanical statistical model for the study of injection-induced seismicity (Nespolia et al., 2015). With TOUGH2-Seed, the authors were able to model several mechanisms influencing each other during and after the injection phase.

9 CONCLUDING REMARKS

After the first development of the TOUGH-FLAC simulator 15 years ago, at least 15 additional TOUGH-based geomechanics models have appeared in the literature (Table 1).

Seven of those involve linking TOUGH2 to an in-house developed or open source finite element code, using sequential coupling techniques as in TOUGH-FLAC, but with access to the source code for the geomechanics part. One of the main motivations related to those developments is the access to the source code and the potential of more efficient coupling as well as the possibility of running the codes together on computer clusters. Among the codes linking TOUGH to an in-house or open source finite element code, TOUGH-ROCMECH is the one that has been applied most extensively to date. Most of these finite element codes are limited to linear poro-elasticity, although ROCMECH includes some elasto-plasticity with Drucker-Prager and Mohr-Coulomb constitutive models. To extend such geomechanics codes to more sophisticated constitutive models that are currently available in FLAC3D will require a substantial effort, but is feasible. TOUGH-CSM includes an unorthodox mechanical approach that with the current addition for calculation of the full stress tensor can be an efficient and useful approach for modeling large systems. TOUGH-based geomechanics models based on codes with access to the source code, such as TOUGH-ROCMECH and TOUGH-CSM, is expected to have increased user basis as more advanced constitutive geomechanics models and processes can be added along with their applications on large computer clusters.

TOUGH-FLAC still remains by far the most applied TOUGH-based geomechanics model. It is the combination of the TOUGH2 library of fluid equations-of-states (EOS) and the FLAC3D library of geomechanical constitutive models that make it possible to extend TOUGH-FLAC to new areas of research and geo-engineering applications within a relatively short time. The fact that FLAC3D only runs under Windows has been viewed as a bottleneck since it cannot be ported to large computer clusters to reduce the computation time. However, the computation time is only one part of the effort. Extension into a new research area or other types of geological media usually involves development and implementation of new constitutive models, to build the mesh and populate the model with material properties, boundary conditions, to run the models, to interpret the results and to publish it in scientific journals. FLAC3D has the user interface and flexible meshing and post-processing capabilities that can be used to construct models for both FLAC3D and TOUGH in an efficient way. A Linux and MPI version of FLAC3D is planned to be developed in the next few years (personal communication with Itasca, April, 2016). This could be very beneficial for being able to run large scale problems, though there are issues on how to deal with the sequential coupling of codes on large-scale computer clusters.

Currently there is a need for effective model simulations of fracturing and fracture propagation in heterogeneous geological media. The ability to model discrete fracture propagation in 2D has been demonstrated for TOUGH-RDCA; the fractures can propagate through the mesh without the need for remeshing. A 3D version of RDCA is under development, but this will require substantial effort and 3D fracture propagation through a 3D heterogeneous rock mass will be challenging. Discrete fracture propagation has also been demonstrated for TOUGH-ROCMECH, in 3D, but limited to a pre-defined path, such as vertical fracture along the boundary of the model domain. Other approaches, such as TOUGH-UDEC and TOUGH-PyLith, could be useful additions for modeling complex hydraulic stimulations and induced seismicity. TOUGH-RBSN has the potential for modeling complex fracturing processes in 3D in heterogeneous geological media, though more developments are required before it can be applied for large-scale systems. The dependency of mesh orientation and size that are typically associated with hydraulic fracturing modeling will also have to be investigated when applying these TOUGH-based hydraulic fracturing models.

Finally, TOUGH-based geomechanics models enabling modeling of coupled THMC (through TOUGHREACT) as well as multi-physics joint inversion (trough ITOUGH), are areas of active research in which significant developments and applications are expected to take place in the coming years. TOUGH-based geomechanics models such as TOUGH-FLAC, TOUGH-

ROCMECH, TOUGH-CSM, TOUGH-RDCA, TOUGH-RBSN, are fully compatible to be extended for linking geomechanics to TOUGHREACT and ITOUGH. These TOUGH-based geomechanics models are complementary in terms of capabilities and application areas and the choice of model for a specific application will always be up to the user based on experience with different models, their capability and availability.

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REFERENCES

Asahina, D., Bolander, J.E., 2011. Voronoi-based discretizations for fracture analysis of particulate materials. Powder Technology 213, 92–99.

Asahina, D., Houseworth, J.E., Birkholzer, J.T., Rutqvist, J., Bolander, J.E., 2014. Hydro-mechanical model for wetting/drying and fracture development in geomaterials. Computers & Geosciences 65, 13–23.

Blanco-Martín, L., Rutqvist, J., Birkholzer, J.T., 2015a. Long-term modelling of the thermal-hydraulic-mechanical response of a generic salt repository for heat-generating nuclear waste. Engineering Geology 193, 198–211.

Blanco-Martín, L., Wolters, R., Rutqvist, J., Lux K.-H., Birkholzer, J.T., 2015b. Comparison of two simulators to investigate thermal-hydraulic-mechanical processes related to nuclear waste isolation in saliniferous formations. Computers & Geotechnics 66, 219–229.

Blanco-Martín, L., Rutqvist, J., Doughty, C., Zhang, Y., Oldenburg C., 2015c. iTOUGH-FLAC modeling of thermal-hydraulic-mechanical processes related to steam-assisted heavy oil recovery from diatomite. Proceedings of the TOUGH Symposium 2015, Lawrence Berkeley National Laboratory, Berkeley, California.

Blanco-Martín, L., Wolters, R., Rutqvist, J., Lux, K.-H., Birkholzer, J.T., 2016. Thermal–hydraulic–mechanical modeling of a large-scale heater test to investigate rock salt and crushed salt behavior under repository conditions for heat-generating nuclear waste. Computers & Geotechnics 77, 120–133.

Calder, N., Avis, J., Kremer, E., Walsh, R., 2015. Application of 1D hydromechanical coupling in TOUGH2 to a deep geological repository glaciation scenario. Proceedings of the TOUGH Symposium 2015, Lawrence Berkeley National Laboratory, Berkeley, California.

Cappa, F., Rutqvist, J., 2012. Seismic rupture and ground accelerations induced by CO_2 injection in the shallow crust. Geophysical Journal International 190, 1784–1789.

Figueiredo, B., Tsang, C.F., Rutqvist, J., Bensabat, J., Niemj, A., 2015. Coupled hydro-mechanical processes and fault reactivation induced by CO_2 Injection in a three-layer storage formation. International Journal of Greenhouse Gas Control 39, 432–448.

Finsterle, S., 2015. What’s new in iTOUGH2?. Proceedings of the TOUGH Symposium 2015, Lawrence Berkeley National Laboratory, Berkeley, California.

Finsterle, S., Zhang ,Y., 2011. Solving iTOUGH2 simulation and optimization problems using the PEST protocol. Environmental Modelling and Software 26, 959–968.

Gosavi, S., Swenson, D., 2005. Architecture for a coupled code for multiphase fluid flow, heat transfer and deformation in porous rock, Proceedings of the Thirtieth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 31-February 2, 2005.

Hu, L., Winterfeld, P.H., Fakcharoenphol, P., Wu, Y.-S., 2013. A novel fully-coupled flow and geomechanics model in enhanced geothermal reservoirs. Journal of Petroleum Science and Engineering 107, 1–11.

Huang, Z.-Q., Winterfeld, P.H., Xiong, Y., Wu, Y.-S., Yao, J., 2015. Parallel simulation of fully-coupled thermal-hydro-mechanical processes in CO_2 leakage through fluid-driven fracture zones. International Journal of Greenhouse Gas Control 34, 39–51.

Hurwitz, S., Christiansen, L.B., Hsieh, P.A., 2007. Hydrothermal fluid flow and deformation in large calderas: inferences from numerical simulations. Journal of Geophysical Research 112, BO2206.

Itasca, 2012. FLAC3D V5.0, Fast Lagrangian Analysis of Continua in 3 Dimensions, User’s Guide. Itasca Consulting Group, Minneapolis, Minnesota.

Izadia, G., Elsworth, D., 2014. Reservoir stimulation and induced seismicity: Roles of fluid pressure and thermal transients on reactivated fractured networks. Geothermics 51, 368–379.

Izadia, G., Elsworth, D., 2015. The influence of thermal-hydraulic-mechanical- and chemical effects on the evolution of permeability, seismicity and heat production in geothermal reservoirs. Geothermics 53, 385–395.

Jeanne, P., Guglielmi, Y., Cappa, F., Rinaldi, A.P., Rutqvist, J., 2014a. The effects of lateral property variations on fault-zone reactivation by fluid pressurization: application to CO_2 pressurization effects within major and undetected fault zones. Journal of Structural Geology 62, 97-108.

Jeanne, P., Rutqvist, J., Dobson, P.F., Walters, M., Hartline, C., Garcia, J., 2014b. The impacts of mechanical stress transfers caused by hydromechanical and thermal processes on fault stability during hydraulic stimulation in a deep geothermal reservoir. International Journal of Rock Mechanics & Mining Sciences 72, 149–163.

Jeanne, P., Rutqvist, J., Vasco, D., Garcia, J., Dobson, P.F., Walters, M., Hartline, C., Borgia A., 2014c. A 3D hydrogeological and geomechanical model of an Enhanced Geothermal System at The Geysers, California. Geothermics 51, 240–252.

Jeanne, P., Rutqvist, J., Hartline, C., Garcia, J., Dobson, P.F., Walters, M., 2014d. Reservoir structure and properties from geomechanical modeling and microseismicity analyses associated with an enhanced geothermal system at The Geysers, California. Geothermics 51, 460–469.

Jeanne, P., Rutqvist, J., Rinaldi, A.P., Dobson, P.F., Walters, M., Hartline, C., Garcia, J., 2015a. Seismic and aseismic deformations and impact on reservoir permeability: The case of EGS stimulation at The Geysers, California, USA. Journal of Geophysical Research Solid Earth 120, 7863–7882.

Jeanne, P., Rutqvist, J., Dobson, P.F., Garcia, J., Walters, M., Hartline, C., Borgia, A., 2015b. Geomechanical simulation of the stress tensor rotation caused by injection of cold water in a deep geothermal reservoir. Journal of Geophysical Research Solid Earth 120, 8422–8438.

Ji, L., Settari, A., Sullivan, R.B., 2009. A novel hydraulic fracturing model fully coupled with geomechanics and reservoir simulation. SPE Journal 14, 423–430.

Kim, J., 2010. Sequential methods for coupled geomechanics and multiphase flow. Ph.D. Thesis, Department of Energy Resources Engineering, Stanford University, California, 264 pp.

Kim, J., Moridis, G.J., 2013. Development of the T+M coupled flow–geomechanical simulator to describe fracture propagation and coupled flow–thermal–geomechanical processes in tight/shale gas systems. Computers & Geosciences 60, 184–198.

Kim, J., Moridis, G.J., 2015. Numerical analysis of fracture propagation during hydraulic fracturing operations in shale gas systems. International Journal of Rock Mechanics & Mining Sciences 76, 127–137.

Kim, J., Tchelepi, H.A., Juanes, R., 2009. Stability, accuracy and efficiency of sequential methods for coupled flow and geomechanics. In: SPE reservoir simulation symposium, 2009 [Paper 119084].

Kim, J., Tchelepi,. H.A., Juanes, R., 2011. Stability and convergence of sequential methods for coupled flow and geomechanics: fixed-stress and fixed-strain splits. Computer Methods in Applied Mechanics and Engineering 200, 1591–1606.

Kim, J., Moridis, G.J., Yang, J., Rutqvist, J., 2012. Numerical studies on two-way coupled fluid flow and geomechanics in hydrate deposits, Society of Petroleum Engineers. SPE-141304-PA, SPE Journal 17, 485–501.

Kim, J., Sonnenthal, E., Rutqvist, J., 2012. A modeling and sequential numerical algorithms of coupled fluid/heat flow and geomechanics for multiple porosity materials. International Journal of Numerical Methods in Engineering 92, 425–456.

Kim, H.-M., Rutqvist, J., Jeong, J.-H., Choi, B.-H., Ryu, D.-W., Song, W.-K., 2013. Characterizing excavation damaged zone and stability of pressurized lined rock caverns for underground compressed air energy storage. Rock Mechanics and Rock Engineering 46, 1113–1124.

Kim, K., Rutqvist, J., Nakagawa, S., Houseworth, J., Birkholzer, J., 2015a. Simulation of fluid-driven fracturing within discrete fracturing within discrete fracture networks using TOUGH-RBSN. Proceedings of the TOUGH Symposium 2015, Lawrence Berkeley National Laboratory, Berkeley, California.

Kim, J., Sonnenthal, E., Rutqvist, J., 2015b. A sequential implicit algorithm if chemo-thermo-poro-mechanics for fractured geothermal reservoir. Computers & Geosciences 76, 59–71.

Konstantinovskaya, E., Rutqvist, J., Malo, M., 2014. CO_2 storage and potential fault instability in the St. Lawrence Lowlands sedimentary basin (Quebec, Canada): Insights from coupled reservoir-geomechanical modeling. International Journal of Greenhouse Gas Control 22, 88–110.

Lee, J., Min, K.-B., Rutqvist, J., 2015. TOUGH-UDEC simulator for the coupled multiphase fluid flow, heat transfer, deformation in fracture porous media. Proceedings of 13th Congress of the ISRM, Montreal, Quebec, Canada, May 10 - 13, 2015.

Lei, H., Xu, T.F., Jin, G., 2015. TOUGH2Biot – A simulator for coupled thermal–hydrodynamic–mechanical processes in subsurface flow systems: Application to CO_2 geological storage and geothermal development. Computers & Geosciences 77, 8–19.

Loschetter, A., Smai, F., Sy, S., Burnol, A., Leynet, A., Lafortune, S., Thoraval, A., 2012. Simulation of CO_2 storage in coal seams: coupling of TOUGH2 with the solver for mechanics Code_Aster, Proceedings of the TOUGH Symposium 2012, Lawrence Berkeley National Laboratory, Berkeley, California.

Lux, K.-H., Rutenberg, M., Seeska, R., Düsterloh, U., 2014. Kopplung der Software codes FLAC3D und TOUGH2 in Verbindung mit in situ-, laborativen und numerischen Untersuchungen zum thermisch-hydraulisch-mechanisch gekoppelten Verhalten von Tongestein unter Endlagerbedingungen. TU Clausthal; 2014 [Final Rep BMWi-Proj 02E11041].

Mainguy, M., Longuemare, P., 2002. Coupling fluid flow and rock mechanics: Formulations of the partial coupling between reservoir and geomechanics simulators. Oil & Gas Science and Technology – Rev IFP 57, 355–367.

Mazzoldi, A., Rinaldi, A.P., Borgia, A., Rutqvist, J., 2012. Induced seismicity within geologic carbon sequestration projects: Maximum earthquake magnitude and leakage potential. International Journal of Greenhouse Gas Control 10, 434–442.

Miah, M., Blanco-Martín, L., Foxall, W., Rutqvist, J., Rinaldi, A.P., Mullen, C., 2015. Development of a hydro-geomechanical model to simulate coupled fluid flow and reservoir geomechanics, Proceedings of the TOUGH Symposium 2015, Lawrence Berkeley National Laboratory, Berkeley, California.

Mikelíc, A., Wang, B., Wheeler, M.F., 2014. Numerical convergence study of iterative coupling for coupled flow and geomechanics. Computers & Geosciences 18, 325–341.

Minkoff, S.E., Stone, C.M., Bryant, S., Peszynska, M., Wheeler, M.F., 2003. Coupled fluid flow and geomechanical deformation modeling, Journal of Petroleum Sciences and Engineering 38, 37–56.

Nespolia, M., Rinaldi, A.P., Wiemer, S., 2015. TOUGH2-SEED: A coupled fluid flow and mechanical statistical model for the study of injection-induced seismicity. Proceedings of the TOUGH Symposium 2015, Lawrence Berkeley National Laboratory, Berkeley, California.

Noorishad, J, Ayatollahi, M.S., Witherspoon, P.A., 1982. A finite element method for coupled stress and fluid flow analysis of fractured rocks. International Journal of Rock Mechanics and Mining Sciences 19, 185–193.

Pan, P.-Z., Rutqvist, J., Feng, X.-T., Yan, F., 2013. Modeling of caprock discontinuous fracturing during CO_2 injection into a deep brine aquifer. International Journal of Greenhouse Gas Control 19, 559–575.

Pan, P.-Z., Rutqvist, J., Feng, X.-T., Yan, F., 2014a. An approach for modeling rock discontinuous mechanical behavior under multiphase fluid flow conditions. Rock Mechanics and Rock Engineering, 47, 589–603.

Pan, P.-Z., Rutqvist, J., Feng, X.-T., Yan, F., Jiang, Q., 2014b. A discontinuous cellular automaton method for modeling rock fracture propagation and coalescence under fluid pressurization without remeshing. Rock Mechanics and Rock Engineering 47, 2183–2198.

Pan, P.-Z., Rutqvist, J., Feng, X.-T., Feng, Yan, F., 2014c. TOUGH–RDCA modeling of multiple fracture interactions in caprock during CO_2 injection into a deep brine aquifer. Computers & Geosciences 65, 24–36.

Previost, J.H., 2013. One-way versus two-way coupling in reeservoir-geomechanical models. in Poromechanics V: Proceedings of the Fifth Biot Conference on Poromechanics, Vienna, Austria, July 10-12, 2013.

Pruess, K., Oldenburg, C., Moridis, G., 2012. TOUGH2 user's guide, version 2.1, LBNL-43134 (revised), Lawrence Berkeley National Laboratory, Berkeley, California

Rinaldi, A.P., Vilarrasa, V., Rutqvist, J., Cappa, F., 2015a. Fault reactivation during CO_2 sequestration: Effects of well orientation on seismicity and leakage. Greenhouse Gas Sciences and Technology 5, 1–12.

Rinaldi, A.P., Rutqvist, J., Sonnenthal, E.L., Cladouhos, T.T., 2015b. Coupled THM modeling of hydroshearing stimulation in tight fractured volcanic rock. Transport in Porous Media 108, 131–150.

Rinaldi, A.P., Rutqvist, J., Finsterle, S., Liu, H.-H., 2015c. Inverse modeling of coupled fluid flow and geomechanics with iTOUGH-PEST and TOUGH-FLAC: Application to In Salah CO_2 storage site. Proceedings of the TOUGH Symposium 2015, Lawrence Berkeley National Laboratory, Berkeley, California.

Rinaldi, A.P., Jeanne, P., Rutqvist, J., Cappa, F., Guglielmi, Y., 2014a. Effects of fault-zone architecture on earthquake magnitude and gas leakage related to CO_2 injection in a multilayered sedimentary system. Greenhouse Gases: Science and Technology 4, 99-120.

Rinaldi, A.P., Rutqvist, J., Cappa, F., 2014b. Geomechanical effects on CO_2 leakage through fault zones during large-scale underground injection. International Journal of Greenhouse Gas Control 20, 117–131.

Rinaldi, A.P., Rutqvist, J., 2013. Modeling of deep fracture zone opening and transient ground surface uplift at KB-502 CO_2 injection well, In Salah, Algeria. International Journal of Greenhouse Gas Control 12, 155–167.

Rohmer, J., Seyedi, D.M., 2010. Coupled large scale hydromechanical modelling for caprock failure risk assessment of CO_2 storage in deep saline aquifers. Oil & Gas Science and Technology – Rev IFP 65, 503–517.

Rutqvist, J., 2011. Status of the TOUGH-FLAC simu-lator and recent applications related to coupled fluid flow and crustal deformations. Computers & Geosciences, 37, 739–750.

Rutqvist, J., Stephansson, O., 2003. The role of hydromechanical coupling in fractured rock engineering. Hydrogeology Journal 11, 7–40.

Rutqvist, J., Tsang, C.-F., 2002. A study of caprock hydromechanical changes associated with CO_2 injection into a brine aquifer. Environmental Geology 42, 296–305.

Rutqvist, J., Tsang, C.-F., 2003a. TOUGH-FLAC: A numerical simulator for analysis of coupled thermal-hydrologic-mechanical processes in fractured and porous geological media under multi-phase flow conditions. Proceedings of the TOUGH symposium 2003, Lawrence Berkeley National Laboratory, Berkeley, May 12–14.

Rutqvist, J., Tsang, C.-F., 2003b. Analysis of thermal-hydrologic-mechanical behavior near an emplacement drift at Yucca Mountain. Journal of Contaminant Hydrology 62–63, 637–652.

Rutqvist, J., Tsang, C.-F., 2012. Multiphysics processes in partially saturated fractured rock: Experiments and models from Yucca Mountain. Reviews of Geophysics 50, RG3006, 2012.

Rutqvist, J., Wu, Y.-S., Tsang, C.-F., Bodvarsson, G., 2002. A Modeling Approach for Analysis of Coupled Multiphase Fluid Flow, Heat Transfer, and Deformation in Fractured Porous Rock. International Journal Rock Mechanics & Mining Sciences 39, 429–442.

Rutqvist, J., Kim, H.-M., Ryu, D.-W., Synn, J.-H., Song, W.-K., 2012a. Modeling of coupled thermodynamic and geomechanical performance of underground compressed air energy storage in lined rock caverns. International Journal of Rock Mechanics & Mining Sciences 52, 71–81.

Rutqvist, J., Moridis, G.J., Grover, T., Silpngarmlert, S., Collett, T.S., Holdich, S.A., 2012a. Coupled multiphase fluid flow and wellbore stability analysis associated with gas production from oceanic hydrate-bearing sediments. Journal of Petroleum Science and Engineering 92–93, 65–81.

Rutqvist, J., Leung, C., Hoch, A., Wang, Y., Wang, Z., 2013. Linked multicontinuum and crack tensor approach for modeling of coupled geomechanics, fluid flow and transport in fractured rock. International Journal of Rock Mechanics and Geotechnical Engineering 5, 18–31.

Rutqvist, J., Cappa, F., Rinaldi, A.P., Godano, M., 2014a. Modeling of induced seismicity and ground vibrations associated with geologic CO_2 storage, and assessing their effects on surface structures and human perception. International Journal of Greenhouse Gas Control 24, 64–77.

Rutqvist, J., Zheng, L., Chen, F., Liu, H.-H., Birkholzer J., 2014b. Modeling of Coupled Thermo-Hydro-Mechanical Processes with Links to Geochemistry Associated with Bentonite-Backfilled Repository Tunnels in Clay Formations. Rock Mechanics and Rock Engineering 47, 167–186.

Rutqvist, J., Dobson, P.F., Garcia, J., Hartline, C., Jeanne, P., Oldenburg, C.M., Vasco D.W., Walters, M., 2015a. The northwest Geysers EGS demonstration project, California: Pre-stimulation modeling and interpretation of the stimulation. Mathematical Geosciences 47, 3–26.

Rutqvist, J., Rinaldi, A.P., Cappa, F., Moridis, G.J., 2015b. Modeling of fault activation and seismicity by injection directly into a fault zone associated with hydraulic fracturing of shale-gas reservoirs. Journal of Petroleum Science and Engineering 127, 377–386.

Settari, A, Mourits, F., 1998. A coupled reservoir and geomechanical simulation system, Society of Petroleum Engineers Journal 3, 219–226.

Smith, T., Sonnenthal, E., Cladouhos, T., 2015. Thermal-hydrological-mechanical modelling of shear stimulation at Newberry Volcano, Oregon. Proceedings of the 49th US Rock Mechanics/Geomechanics Symposium, San Francisco, CA, USA, 28 June- 1 July 2015. American Rock Mechanics Association ARMA, Paper No. 15-680.

Taron, J., Elsworth, D., 2009. Thermal–hydrologic–mechanical–chemical processes in the evolution of engineered geothermal reservoirs. International Journal of Rock Mechanics & Mining Sciences 46, 855–864.

Taron, J., Elsworth, D., Min, K.B., 2009. Numerical simulation of thermal–hydrologic–mechanical–chemical processes in deformable, fractured porous media. International Journal of Rock Mechanics & Mining Sciences 46, 842–854.

Urpi, L., Rinaldi, A.P., Rutqvist, J., Cappa, F., Spiers, C.J., 2016. Dynamic simulation of CO_2-injection-induced fault rupture with 1 slip-rate dependent friction coefficient. Geomechanics for the Energy and Environment (accepted April 28, 2016).

Vilarrasa, V., Rutqvist, J., Blanco-Martín, L., Birkholzer, J., 2015. Use of a dual structure constitutive model for predicting the long-term behavior of an expansive clay buffer in a nuclear waste repository. ASCE's International Journal of Geomechanics D4015005.

.

Walsh, R., Calder, N., Avis, J., 2012. A Simple Implementation of 1D Hydromechanical Coupling In TOUGH2, Proceedings of the TOUGH Symposium 2012, Lawrence Berkeley National Laboratory, Berkeley, California.

Walsh, R., Nasir, O., Calder, N., Sterling, S., Avis J., 2015. Combining TOUGH2 and FLAC3D to solve problems in underground natural gas storage. Proceedings of the TOUGH Symposium 2015, Lawrence Berkeley National Laboratory, Berkeley, California.

Winterfeld, P.H., Wu, Y.-S., 2012. Development of an advanced thermal-hydrological-mechanical model for CO_2 storage in porous and fractured saline aquifers. Proceedings of the TOUGH Symposium 2012, Lawrence Berkeley National Laboratory, Berkeley, California, 2012.

Winterfeld, P. H., Wu, Y.-S., 2014. Simulation of CO_2 sequestration in brine aquifers with geomechanical coupling. In Computational Models for CO_2 Sequestration and Compressed Air Energy Storage, edited by J. Bundschuh and R. Al-Khoury, Chapter 8, CRC Press, New York, NY, 2014.

Winterfeld, P.H., Wu, Y.-S., 2015. A coupled flow and geomechanics simulator for CO_2 storage in fracture reservoirs. Proceedings of the TOUGH Symposium 2015, Lawrence Berkeley National Laboratory, Berkeley, California.

Zhang, R., Yin, X., Winterfeld, P.H., Wu, Y.-S., 2012. A fully coupled model of nonisothermal multiphase flow, geomechanics, and chemistry during CO_2 sequestration in brine aquifers. Proceedings of the TOUGH Symposium 2012. Lawrence Berkeley National Laboratory, California.

Zheng, L., Rutqvist, J., Liu, H.-H., Birkholzer, J.T., Sonnenthal E., 2014. Model evaluation of geochemically induced swelling/shrinkage in argillaceous formations for nuclear waste disposal. Applied Clay Science 97–98, 24–32.

Zheng, L., Rutqvist, J., Birkholzer, J.T., Liu, H.H., 2015. On the impact of temperatures up to 200ºC in clay repositories with bentonite engineer barrier systems: a study with coupled thermal, hydrological, chemical, and mechanical modeling. Engineering Geology 197, 278–295.

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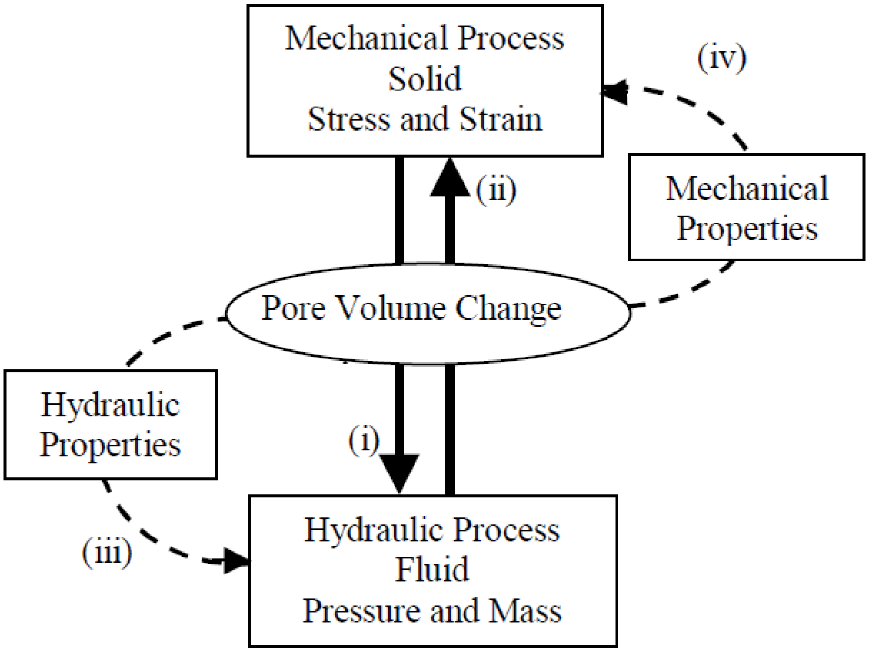

Figure 1. Hydromechanical couplings in geological media; (i) and (ii) are direct couplings through pore volume interactions, while (iii) and (iv) are indirect couplings through changes in material properties (Rutqvist and Stephansson, 2003).