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Review Article

Coupled processes in rock mass performance with emphasis on nuclear waste isolation ☆

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Abstract

Driven by the needs of engineered underground systems, the field of rock mechanics is evolving to address the interactions of in situ mechanical, thermal, hydrologic, and chemical processes and their effects on system performance. Important technical issues include understanding how the relevant loads and gradients drive in situ processes; rock mass variability, discontinuity, and heterogeneity; process and parameter scale dependence; and the degree of coupling between processes. Major challenges include scaling information from short-duration laboratory tests up to long-term, full-scale system performance and the lack of experimental investigations or simulations of fully coupled thermal-mechanical-hydrologic-chemical behavior. Technical trends and opportunities that may benefit rock engineering include applied research in reactive geochemistry, information technology for measurement systems, and modeling and monitoring combined in an observational method to improve system performance.

1. Introduction

Growing human needs for resource extraction, transportation, storage, waste disposal, and security demand the successful performance of subsurface systems and structures. As the spatial dimensions, time scales, and performance requirements of engineered underground systems become more demanding, natural and induced in situ processes affect performance in increasingly significant ways. When an underground chamber receives heated or cooled materials, for example, it may experience mechanical, thermal, hydrologic, and chemical processes that interact to influence the overall performance of the structure. These challenges are particularly acute in nuclear waste isolation projects, which have extremely demanding performance requirements.

The well-developed field of rock mechanics is evolving to meet these challenges by addressing the full complement of process interactions, or coupled processes, that affect rock mass behavior. Fig. 1 sketches some of the potential interactions of thermal, mechanical, hydrologic, and chemical processes. Bold arrows emphasize interactions that are of potentially greater engineering significance. This paper surveys recent refereed literature to evaluate our understanding of coupled processes in rock mechanics and to frame future directions for rock engineering in large scale and very long-term applications such as nuclear waste isolation.

On a fundamental level, processes that affect rock mass performance include:

- Thermal heating and cooling. Researchers have examined the effects of heating on underground structures and instrumentation. Investigations of cooling effects are less common. Our survey focused on coupled processes that involved moderate temperature changes of up to about $\pm 200°C$.
- Mechanical effects. Our survey included investigations of coupled processes that involved rock mass stress perturbations of up to a few tens of MPa,

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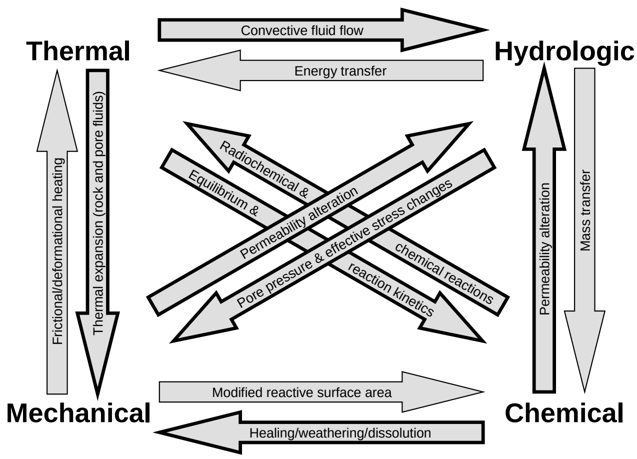

Fig. 1. Effects of coupled in situ processes in rock mass behavior. Bold arrows suggest processes of potentially greater engineering significance.

corresponding to an overburden depth of a few to several hundreds of meters.

- Hydrologic flow. Gas and water are important media that can transport contaminants from waste sites to human and ecological receptors. Given the difficulty of predicting contaminant transport in porous and fractured media, relatively few publications have examined coupling with other rock properties. Our survey included research into process interactions that quantified hydrologic behavior.
- Chemical effects. Processes such as fracture healing, mineral dissolution or precipitation, weathering-induced weakening, or contaminant mobilization and transport each have implications for the long-term performance of engineering projects in rock. Our survey included investigations of coupled interactions that included chemical effects.
- Microbial effects and radiological effects. Microbial and radiological processes may each affect rock chemistry on a local scale, but our survey found no refereed literature on either topic in the context of coupled rock mass processes or rock engineering.

Much of the research in this area over the past twenty to thirty years has been performed under the auspices of the STRIPA, Spent Fuel Test—Climax, Yucca Mountain, INTERVAL, DECOVALEX, and similar projects. Important experimental work at the Nevada Test Site, AECL Underground Research Laboratory, Yucca Mountain, Kamaishi, Äspö, and other research facilities has helped advance our understanding of coupled in situ processes. Most of this work has been reported in peer-reviewed journal articles, books, conference proceedings, and project documents. However, conference proceedings are usually less detailed and project reports are often less readily available than references such as journal articles. Therefore, in preparing this survey, we conducted an extensive electronic literature search and screened over 100 peer-reviewed journal papers and books to select 69 representative articles for the References listing. The selected articles include laboratory and field scale experimental work as well as a range of numerical modeling efforts. An Introduction to References section furnishes brief annotations for 23 of the most valuable references to provide starting points for further reading.

2. Technical issues

Projects as diverse as transportation tunnels [1,2], caverns for liquefied gas storage [3], geothermal energy extraction [4], and in situ coal gasification [5] are influenced by coupled processes on rock mass performance. Projects with unusually long-term performance requirements, such as geologic repositories for nuclear waste isolation, are particularly susceptible to their impact [6,7, and others]. Major rock engineering projects must deal with relevant coupled processes on a case by case basis. For example:

- Nuclear waste isolation in geologic repositories must meet defined performance goals over an extraordinarily long project life cycle. Design, operation, and optimization of the repository systems require adequate understanding of chemical, hydrologic, mechanical, and thermal loading and unloading conditions.
- Storage of cryogenic fluids (such as liquefied natural gas) in caverns involves significant thermal unloading of the host rock along with related mechanical, chemical, and hydrologic effects. Pressurized cryogenic fluids will change the stress field around the cavern, slow the rates of chemical reactions, and perhaps alter rock strength as water freezes and expands in cracks and fractures. This thermal perturbation is opposite to the heating caused by nuclear waste emplacement, but many of the measurement issues and some of the modeling issues are similar.
- Thermally enhanced oil recovery and in situ coal gasification use engineered thermal processes that rapidly heat parts of the rock mass while maintaining fluid conductivity to extract the oil or gas. Although the thermal gradients may be steeper and more localized than those encountered with nuclear waste emplacement, some of the material and process-related issues are similar.

Natural and imposed loads and gradients (for example, thermal loads or chemical gradients) drive in situ coupled processes. Some processes, such as thermal

Table 1
Qualitative comparison of basic processes affecting rock mass performance

	Process	Typical site parameter variability	Ability to model field data
T	Thermal	Less than 25%	Good
M	Mechanical	Locally up to factor of 2–5	Fair
H	Hydrologic	Orders of magnitude	Fair to poor
C	Chemical	Orders of magnitude	Problematic

diffusion, behave rather predictably, even in fractured, heterogeneous rock. This is because coefficients of thermal diffusivity do not vary much, compared to other parameters, between different types of geologic materials. Other processes, such as hydrologic or chemical phenomena, are more difficult to predict because parameter values, discontinuities, and heterogeneities may vary by orders of magnitude, and are impossible to determine by characterization tools over relevant spatial scales. Table 1 qualitatively compares four major types of processes.

Process coupling occurs over a wide range of time and length scales. Fig. 2 compares the temporal and spatial scales of experiments, engineered structures, and natural phenomena involving coupled processes in rock. The time scale reflects the typical duration or life cycle of an experiment or project, while the length scale gives a sense of geometric size. The chart shows that we measure most rock properties and processes in experiments and tests that are orders of magnitude smaller and of much shorter duration than engineering projects. Together with the complications of site heterogeneity and parameter variability, this makes it difficult to predict and extrapolate the effects of coupled processes to larger scales and over time. This figure also suggests that empirical experience from mining activities and civil structures is not as relevant as we might wish for larger scale and longer duration nuclear waste repositories.

Another aspect of Fig. 2 is the scale-dependence of various processes. The line labeled Molecular Diffusion represents the characteristic distance a dissolved molecule will diffuse in water over a specified time using the relationship that diffusion distance scales as the square root of the product of diffusivity and time. Molecular diffusion can produce significant mixing effects in laboratory experiments because of their small length and time scales. However, larger scale applications, such as civil structures, plot above or to the left of the diffusion line, indicating that diffusion processes require more time than the performance life of the project to operate at that length scale. Thus, other processes or process interactions are likely to overshadow the effects of molecular diffusion per se. Another curve, representing Thermal Diffusion, aligns more closely with projects ranging from field scale experiments to nuclear waste repositories. This suggests that thermal energy transfer is likely to have a significant influence on scales comparable to the size and duration of a wider range of projects. Finally, a line representing Advective Flow at a velocity of one meter per year helps delineate the

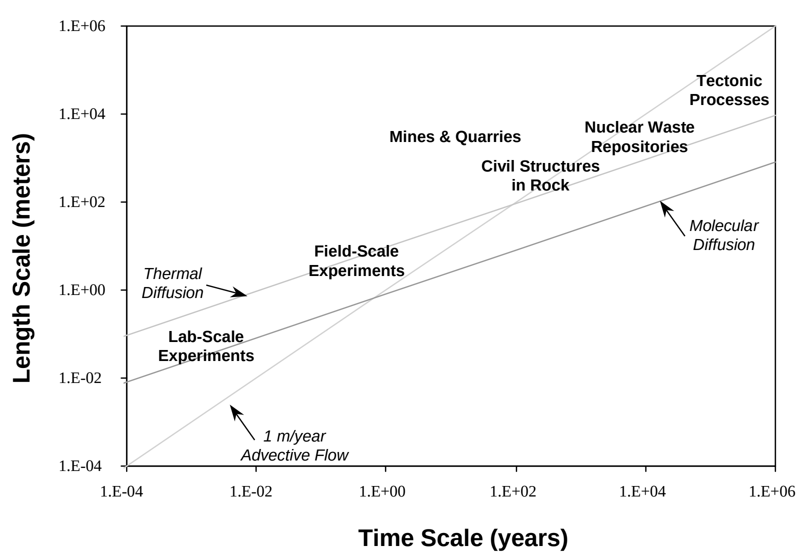

Fig. 2. Typical temporal and spatial scales of experiments, engineered structures, and natural phenomena involving coupled processes in rock.

possible importance of water flow. The line intersects many of the relevant systems encountered in rock masses, but appears more likely to impact full scale engineering projects than field or lab scale experiments.

Scale-up is a vital issue in the analysis, design, construction, and operation of large scale engineering systems. At the smaller scales typical of laboratory conditions, numerous controls are possible on material properties, mechanical loading, and thermal and hydrologic fluxes. As the scale of the system increases, additional processes as well as uncertainties in properties, fractures, heterogeneities, loads, and fluxes all come into play. In general, the scale up of engineering systems proceeds in steps of about an order of magnitude. For example, at Yucca Mountain, heater test on a nominal 10-m scale block followed tests on meter scale blocks. It is unlikely, though, that short-term results from a 10-meter scale test can provide empirical data or calibration data for numerical models to predict performance at the full repository scale.

Further technical challenges involve the degrees of coupling between in situ processes, and the difficulty of developing and comparing good data with good models [8,9] as a basis for geoscience and engineering applications. Fig. 3 compares the scope of a number of recent refereed journal articles involving coupled processes in rock or rock materials. The numbers shown in the chart correspond to references listed at the end of this paper; bold numbers indicate articles highlighted in the Introduction to References. The "Experimental Data" axis of Fig. 3 indicates how (or if) a paper includes data from physical tests or experiments. Movement to the right along the axis denotes measurements and results from increasingly complicated process interactions. Similarly, the "Modeling or Analysis" axis indicates how a paper includes numerical simulations or analyses (not data).

The tally of references in each bin of Fig. 3 reflects the apparent interests of the research community over the past couple of decades. This is a subjective assessment, since our survey looked at peer-reviewed journal articles and books, and did not include symposium papers or extended abstracts. Regardless, the absence of peer-reviewed journal articles from the top row and right-hand column of the chart seems to outline the limits of the current state of the art. Further, if the articles gave equal weight to data and models, they would tend to align along the diagonal of the matrix. More articles appear in the upper left half than in the lower right half of the matrix, suggesting that modeling is getting more attention than measurements. Perhaps this reflects the expense of field tests, but it also suggests the need for additional laboratory and field-scale investigations of coupled processes.

3. Trends and opportunities

Rock engineering is evolving to encompass mechanical, hydrologic, thermal, and, to a limited extent, chemical processes in the design and performance of structures and systems in rock. These processes unavoidably couple, or interact, on a number of spatial and temporal scales, and their importance increases roughly in proportion to the life cycle and performance expected of the project. We could not find a cogent economic analysis of historical trends or the value of research, additional data, or new analyses in addressing coupled processes. Nevertheless, this section briefly outlines areas where current trends in research and

Modeling or Analysis	No Experimental Data Sets	Data for One Process	Data for Two Coupled Processes	Data for Three Coupled Processes	Data for Four Coupled Processes
Four Processes					
Three Processes	**4, 7, 21** 29, 30, 39, 43, 50, 51, 52	**6** 28, 60	**3** 31	**5, 11, 20**	
Two Processes	32, 44, 47, 48, 53, 55, 56, 57, 62, 63, 65, 66, 69	**9, 15, 17** 54, 61	**10, 19, 22, 23** 27, 35, 40, 41, 46, 58, 64, 67	**2**	
Single Process		**14** 26, 45	**18**	**1**	
No Modeling		24, 36	**13** 33, 37, 59, 68	**12, 16** 25, 34, 42, 49	

Experimental Data

Fig. 3. Scope of recent peer-reviewed papers involving coupled processes in rock. The numbers correspond to the reference list [24–69]; the Introduction to References section describes the bold items.

technology may lead to opportunities with practical payoffs for rock engineering: reactive geochemistry, information technology, and modeling and monitoring applied in an observational method to improve system performance.

The importance of chemistry is becoming more widely recognized when discussing coupled processes in rock engineering, particularly for nuclear waste management (Fig. 1). Environmental chemistry has transitioned from an approach based on equilibrium to one that attempts to understand and model kinetics. However, the papers found in this survey included only limited treatment of chemical transformations, either for rock mass weathering or for the coupling between chemical transformations and mechanical and thermal behavior. An extensive body of extant literature on mineral weathering could be adapted and used in rock engineering. Conversely, the investigations of weathering would benefit from a more realistic understanding of thermal, mechanical, and hydrologic loadings in the field rather than continuing to focus on experimental results from testing crushed rock materials in vessels. To take this observation a step further, many rock engineering projects could benefit from a more interdisciplinary approach that includes relevant elements of structural geology, geophysics, and petroleum, mining, or civil engineering. These disciplinary divisions are artifacts of the profession rather than of the rock mass.

New information technologies are creating opportunities for collecting and processing massive data sets. Miniaturized sensors, sensor networking, data telemetry, and the capabilities of computational resources for data pre- and post-processing can support laboratory and field experiments that were previously not feasible. While more sophisticated experimental programs are becoming possible, there needs to be careful consideration of how to represent the data, either visually or statistically, in methods that will expand our understanding of system behavior. Many researchers refer to enhanced computational power leading to improved numerical models that will predict complex behavior, but, as Fig. 3 indicates, the literature is highly populated with numerical studies that lack supporting experimental data. The solution to this dilemma is not in greater processing speed or data storage, but in the use of such tools to help achieve and apply greater understanding.

The ultimate goal in rock engineering for nuclear waste disposal is to develop a system that will isolate these hazardous materials far into the future. The profession is still working towards the appropriate combination of modeling and monitoring for the design, construction, operation, and closure phases of a repository life cycle. Intact rock masses are inherently difficult to characterize and monitor without disturbance, and predictive models are highly uncertain when forced to work from limited data. Information about the properties and behavior of the rock mass will become more readily available during repository excavation; this knowledge base will support greater confidence in predictive models. During repository operations, performance monitoring can provide a basis for improving the models that are used to anticipate future conditions. Finally, when the waste disposal facility is ready for closure, monitoring should be able to verify system performance with some support from modeling activities. Feedback between design/construction/operation, observational data, and model conceptualization and application will provide the most robust path for optimizing underground system performance. Rock engineering as a profession has yet to develop and document a methodology that provides the appropriate combination of monitoring and modeling, but its geotechnical roots in the observational method should help answer this challenge.

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Introduction to References

The annotations below highlight peer-reviewed references that hold particular value for understanding coupled processes in rock mass performance. The reference list that follows this section uses * to designate articles of special interest, and ** for articles of outstanding interest.

- Bérest et al. [10] used a cavern-scale shut-in test to investigate coupled hydrologic and mechanical processes affecting a sealed, brine-filled cavern in bedded salt, and to assess the prospects for leakage and migration during thermal expansion of the brine.
- Börgesson et al. [11] compared laboratory test data with four finite element models for thermo-mechanical-hydrologic behavior of a bentonite buffer material. Initial results were encouraging, and the authors offer suggestions (e.g., longer test durations) to achieve better results.
- Chigira and Oyama [1] studied chemical alteration of rock due to the oxidation of pyrites. Movement of oxygen and water through the rock can significantly affect the strength of chemically altered zones through mineral dissolution or precipitation.

- Chijimatsu et al. [12] described the design, construction, operation, and results of a thermo-mechanical-hydrologic field test involving bentonite buffer material emplaced in a large borehole in fractured rock. This kind of information is vital for properly modeling coupled field tests, and it should be useful for planning and understanding field experiments.
- Dahan et al. [13] used steady-state infiltration tests to examine fracture flow in the vadose zone, and found significant flow variability over time and at different spatial scales. Simple hydrologic models could not replicate the observed unsteady flow behavior.
- Gómez-Hernández et al. [14] conducted a stochastic analysis of an interference test conducted in fractured volcanic tuff. The investigators could simulate most of the transient pressure behavior without resorting to a coupled mechanical-hydrologic model. Nevertheless, this application of stochastic techniques to limited data could set an example for other field situations.
- Hakami [15] performed mechanical-hydrologic modeling for a pumping test and for shaft sinking in fractured rock. The analysis did not need to include mechanical and hydrologic coupling, but this may be an artifact of simplifications in the modeling.
- Hettema et al. [5] examined coupled thermal and hydrologic diffusion processes to understand thermally induced spalling in porous rock. In general, spalling can occur when the rate of thermal heating surpasses the rate of pore pressure dissipation, causing pore pressures to exceed the rock tensile strength. This can be counterintuitive, since strong, low permeability rock could be more susceptible than weak, high permeability rock for this failure mechanism.
- Hudson et al. [6] discussed many aspects of thermo-mechanical-hydrologic processes and modeling, with an emphasis on their relevance to nuclear waste repository design, construction, and performance. This paper provides a starting point for understanding the importance of coupled in situ processes in nuclear waste isolation.
- Kohl et al. [4] modeled thermo-mechanical-hydrologic processes for a hot dry rock geothermal application to show how heat removal can cause rock shrinkage, increase fracture flow, and reduce heat recovery from the rock fracture system.
- Moore et al. [16] investigated fracture healing in granite at elevated temperatures. In their one-dimensional experiments, fracture permeabilities dropped by more than two orders of magnitude over a matter of days. The presence of reactive mineral surfaces (provided by crushed granite) accelerated the healing process.
- The National Research Council [17] provided a broad tutorial on natural, induced, and engineered changes in rock fracture permeability, reviewed their engineering significance, and outlined current research needs. They also suggested moving towards an approach that integrates modeling with actual performance data.
- Neaupane et al. [3] tested and modeled thermo-mechanical-hydrologic processes in one-dimensional freeze/thaw experiments with saturated specimens of tuff and sandstone. This work did not examine hydrologic coupling (i.e., flow processes), but has practical implications for applications such as liquefied natural gas storage in rock caverns.
- Nguyen et al. [18] described four modeling efforts to simulate mechanical-hydrologic rock mass behavior during excavation of a large test borehole in fractured granite. Gross flow behavior and rock mass displacement simulations went well, but pore pressure and borehole deformation calculations were less successful. Model conceptualization was more important than the sophistication of the model for the success of the simulations.
- Nguyen and Selvadurai [19] demonstrated mechanical-hydrologic coupling in the effects of shear deformation on fracture permeability. Initial shear deformation increases permeability because of fracture dilatancy; but continued shearing damages asperities, generates gouge filling, and begins to reduce fracture permeability.
- Oreskes et al. [8] discussed the potential value, shortcomings, and roles of numerical models in earth sciences applications. These authors are not part of the usual circles of engineering discussions, so their perspectives provide a good reality check against the use and abuse of numerical simulators.
- Oyama and Chigira [2] extended their earlier investigation [1] with field data and by modeling weathering effects on rock adjacent to tunnels. This work illustrates the impact of coupled hydrologic-chemical processes on rock mass performance over only a few decades.
- Rutqvist et al. [20] compared four thermo-mechanical-hydrologic models with data from an electric heater test involving a clay buffer in fractured rock. Discrepancies in the comparison seemed to be associated with material interfaces and heterogeneities.
- Selvadurai and Nguyen [21] used a coupled thermo-mechanical-hydrologic model to perform sensitivity analyses of rock mass performance around a hypothetical nuclear waste repository, but did not check their results against field data.
- Steefel and Lichtner [22] presented field data and one-dimensional modeling to examine coupled hydrologic-chemical processes for a natural analog site. They also identified uncertainties in the analysis and in their findings, with implications for nuclear waste repository applications.

- Tsang et al. [7] discussed thermo-mechanical-hydrologic modeling and data needs for the design, operation, and post-closure phases of a repository life cycle. They mentioned but did not address in situ chemical processes.
- Tsang [23] introduced two field tests for thermo-mechanical-hydrologic-chemical processes at Yucca Mountain, NV, and focused on integrating modeling with field measurements for coupled thermal and hydrologic aspects of the tests. Site-specific heterogeneities affected rock mass behavior on a local scale.
- Wawersik [9] discussed the use and validation of numerical models for rock mechanics applications. The cost and difficulty of full-scale field tests suggests broader use of carefully designed laboratory experiments for code validation.

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