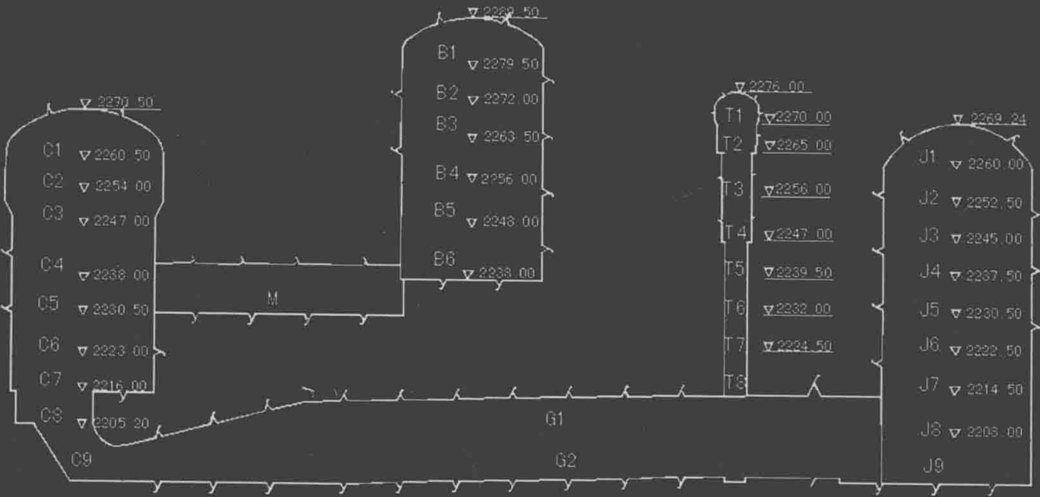

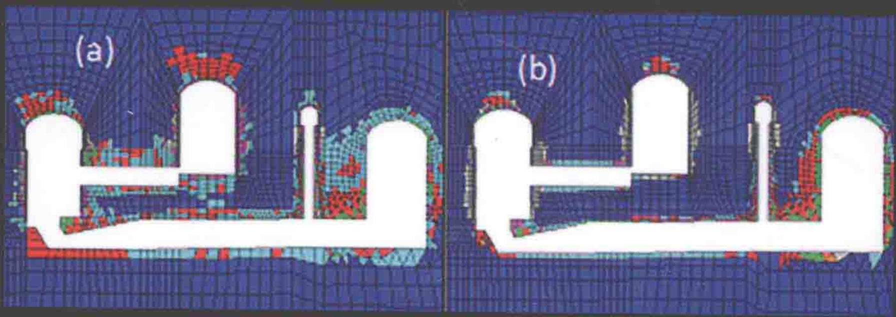

Rock Mechanics and Engineering

Editor: Xia-Ting Feng

Volume 3: Analysis, Modeling & Design

CRC Press
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A BALKEMA BOOK

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Editor

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Foreword

Although engineering activities involving rock have been underway for millennia, we can mark the beginning of the modern era from the year 1962 when the International Society for Rock Mechanics (ISRM) was formally established in Salzburg, Austria. Since that time, both rock engineering itself and the associated rock mechanics research have increased in activity by leaps and bounds, so much so that it is difficult for an engineer or researcher to be aware of all the emerging developments, especially since the information is widely spread in reports, magazines, journals, books and the internet. It is appropriate, if not essential, therefore that periodically an easily accessible structured survey should be made of the currently available knowledge. Thus, we are most grateful to Professor Xia-Ting Feng and his team, and to the Taylor & Francis Group, for preparing this extensive 2017 "Rock Mechanics and Engineering" compendium outlining the state of the art—and which is a publication fitting well within the Taylor & Francis portfolio of ground engineering related titles.

There has previously only been one similar such survey, "Comprehensive Rock Engineering", which was also published as a five-volume set but by Pergamon Press in 1993. Given the exponential increase in rock engineering related activities and research since that year, we must also congratulate Professor Feng and the publisher on the production of this current five-volume survey. Volumes 1 and 2 are concerned with principles plus laboratory and field testing, *i.e.*, understanding the subject and obtaining the key rock property information. Volume 3 covers analysis, modelling and design, *i.e.*, the procedures by which one can predict the rock behaviour in engineering practice. Then, Volume 4 describes engineering procedures and Volume 5 presents a variety of case examples, both these volumes illustrating 'how things are done'. Hence, the volumes with their constituent chapters run through essentially the complete spectrum of rock mechanics and rock engineering knowledge and associated activities.

In looking through the contents of this compendium, I am particularly pleased that Professor Feng has placed emphasis on the strength of rock, modelling rock failure, field testing and Underground Research Laboratories (URLs), numerical modelling methods—which have revolutionised the approach to rock engineering design—and the progression of excavation, support and monitoring, together with supporting case histories. These subjects, enhanced by the other contributions, are the essence of our subject of rock mechanics and rock engineering. To read through the chapters is not only to understand the subject but also to comprehend the state of current knowledge.

I have worked with Professor Feng on a variety of rock mechanics and rock engineering projects and am delighted to say that his efforts in initiating, developing and seeing through the preparation of this encyclopaedic contribution once again demonstrate his flair for providing significant assistance to the rock mechanics and engineering subject and community. Each of the authors of the contributory chapters is also thanked: they are the virtuosos who have taken time out to write up their expertise within the structured framework of the "Rock Mechanics and Engineering" volumes. There is no doubt that this compendium not only will be of great assistance to all those working in the subject area, whether in research or practice, but it also marks just how far the subject has developed in the 50+ years since 1962 and especially in the 20+ years since the last such survey.

John A. Hudson, Emeritus Professor, Imperial College London, UK
President of the International Society for Rock Mechanics (ISRM) 2007–2011

Introduction

The five-volume book "Comprehensive Rock Engineering" (Editor-in-Chief, Professor John A. Hudson) which was published in 1993 had an important influence on the development of rock mechanics and rock engineering. Indeed the significant and extensive achievements in rock mechanics and engineering during the last 20 years now justify a second compilation. Thus, we are happy to publish 'ROCK MECHANICS AND ENGINEERING', a highly prestigious, multi-volume work, with the editorial advice of Professor John A. Hudson. This new compilation offers an extremely wide-ranging and comprehensive overview of the state-of-the-art in rock mechanics and rock engineering. Intended for an audience of geological, civil, mining and structural engineers, it is composed of reviewed, dedicated contributions by key authors worldwide. The aim has been to make this a leading publication in the field, one which will deserve a place in the library of every engineer involved with rock mechanics and engineering.

We have sought the best contributions from experts in the field to make these five volumes a success, and I really appreciate their hard work and contributions to this project. Also I am extremely grateful to staff at CRC Press / Balkema, Taylor and Francis Group, in particular Mr. Alistair Bright, for his excellent work and kind help. I would like to thank Prof. John A. Hudson for his great help in initiating this publication. I would also thank Dr. Yan Guo for her tireless work on this project.

Editor
Xia-Ting Feng
President of the International Society for Rock Mechanics (ISRM) 2011–2015
July 4, 2016

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Numerical Modeling Methods

Chapter 1

Coupled THMC modeling for safety assessment of geological disposal of radioactive wastes: The DECOVALEX project (1992–2015)

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Abstract: This Chapter describes a long-term research effort (1992 to the present) on coupled THMC processes in geological systems in the context of the safe geological disposal of radioactive wastes: the DECOVALEX project (DEvelopment of COupled models and their VAlidation through EXperiments). This project is a unique international co-operative research project which was initiated in 1991, officially started in 1992, has continued through a number of phases without interruption since then and is still continuing in the time of preparing this chapter by the authors. The overall objective of this research has been the development, validation and application of numerical modeling methods and techniques for the performance and safety assessments of geological disposal of radioactive waste (GDRW) in underground repositories. The cooperation has been financed by national waste management organizations, regulatory bodies and national research institutes and individual universities in Canada, China, Czech Republic, European Commission, Finland, France, Germany, Republic of Korea, Spain, Japan, Sweden, UK and USA. Over the period of 23 years, the project has made impressive advanced researches in the field of coupled THMC (Thermo-Hydro-Mechanical-Chemical) processes in geological systems, especially in fractured crystalline and sedimentary rocks and buffer/backfill materials, through integrated numerical modeling and laboratory and field experiments. The experiments cover scales ranging from laboratory-sized samples to in situ experiments in underground research laboratories (URLs) in different host rocks in different countries. The work has resulted in an impressive number of major developments, as reported in scientific publications and helped to educate and train younger generations of researchers in this field. This Chapter presents the goals, structure, contents and approaches of the project, as well as achievements and lessons learned during this long-term project, at both the fundamental and application levels.

1 INTRODUCTION

The subject of couplings between the thermal (heat transfer), hydrological (fluid flow) and mechanical (stress, deformation, damage and failure) processes in fractured rocks has become an important subject in rock mechanics and engineering since the early 1980s (Tsang, 1987, 1991), mainly due to the modeling requirements for the design and performance assessment of underground radioactive waste repositories, and other engineering fields in which heat transfer and fluid flow play important roles, such as gas/oil recovery, geothermal energy extraction, contaminant migration control and environment impact evaluation in general. In fact, the coupling can be extended to include geological, chemical and biological processes, but the coupled THM (thermo-hydro-mechanical) and coupled THMC (thermo-hydro-mechanical and chemical) processes are the ones most often required in coupled models in rock engineering. The need to couple the processes in geological systems is a reflection of the fact that the processes affect each other, which occurs mainly in two ways. The first is direct coupling in which one process induces the development of another process, representable by a cross term involving both processes in the governing equations. The second way is indirect coupling in which one process changes the property parameters controlling the progress of another process.

In general, the impact of natural or man-made perturbations on rock masses, such as tectonic events, glaciation cycles, drilling, excavations and injections of fluids or solid particles, on the energy and mass transport in rocks cannot be predicted with adequate reliability by considering each process independently without consideration of couplings among the processes involved.

Underground repositories in either crystalline rocks (mostly granites) or sedimentary rocks (mostly clayey rocks) have been considered in many countries worldwide as a potential solution for disposal of radioactive waste. Figure 1 shows a conceptual illustration of a Geological Disposal of Radioactive Waste (GDRW) repository concept developed by SKB, Sweden, based on the concept of multi-barrier system composed of canisters, bentonite buffer, backfill materials (mostly crushed rocks and bentonite mixtures) and the host rock. The host rock represents the geosphere of the system and is often referred to as the far-field of the repository. The canister, bentonite buffer and backfill, placement deposition hole and the transportation tunnel are often referred to as the near-field. The coupled THM/THMC processes in the above conceptual

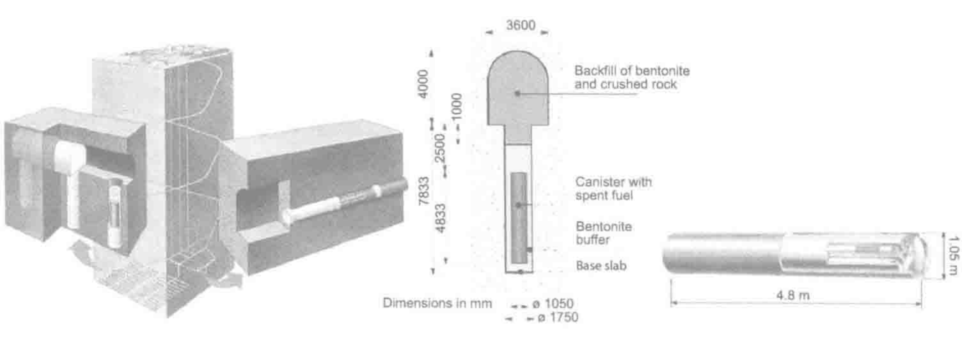

Figure 1 a) The SKB's KBS-3 concept of a Geological Disposal of Radioactive Waste (GDRW) repository in crystalline rocks with alternative vertical or horizontal placement of cast-iron canisters containing the spent fuel surrounded by a bentonite buffer and the host rock; b) the near-field of the repository with canister, bentonite buffer in the placement borehole, and backfill in the transportation tunnels; and c) the canister containing the spent fuel.

GDRW repositories are composed of interactions among mechanisms of energy and mass transport due to: (a) heat generation (radioactive decay by spent fuel) and transfer (by conduction, advection, diffusion and radiation in excavations and materials in the near- and far-fields); (b) flows of geo-fluids (groundwater, gases, steam-vapor and their mixtures) in the porous rock matrix and fracture networks; (c) stress, deformation, damage and failure of all materials in the near- and far-fields; and (d) geochemical processes that affect the generation, evolution and transport of radioactive nuclides in the near- and far-fields. Radionuclide transport (path, time and amount) is the key concern for the safety of the repository concerned.

The coupled THM/THMC processes of geological systems are one of the key issues for the study of GDRW repositories, due to the two most important aspects of any GDRW project.

1. Environmental safety is required for tens of thousands or millions of years, which means that any current laboratory or field experiment lacks the capability for observing and establishing the long-term behavior of the repository system.
2. The multi-scale complexity of the fracture systems, and heterogeneity in general, in rock masses cannot be measured in detail and is difficult to be reliably characterized mathematically in order to support proper analysis of large scale in situ experiments.

These two factors make the predictive mathematical models and associated computational methods the only quantitative means to assess GDRW long-term safety based on fundamental understanding about the interactions among processes, properties and parameters of the whole system over such long time periods before, during and after the repository construction and operation. Owing to the fact that the verification of the reliability of such predictions is possible only for short time behavior of repository design, construction, operation and post-closure monitoring systems. There is a great need that such predictions will be conducted as much as possible carefully and completely without bias because of researchers' background and prior concepts. This is the main motivation for the international co-operative research project DECOVALEX that was initiated in 1991, launched in 1992 and has been continuously extended since then.

Based on a series of initial discussions during 1990–1992, the DECOVALEX project was launched in Stockholm, Sweden, and managed by the Swedish Nuclear Power Inspectorate (SKI). It was originally planned for the period of 1992–1995. The overall objective of the DECOVALEX project was "to increase the understanding of various thermohydromechanical processes of importance for radionuclide release and transport from a repository to the biosphere and how these could be described by mathematical models". The modeling and testing of the coupled THM processes in geological media, which were commonly used in safety assessment of GDRW repositories at that time, was not a mature field of science and technology. The practical objectives were focused on increasing basic understanding of the coupled THM processes, advancing modeling capacities and tools for simulating THM processes in fractured hard rocks with validations against well controlled, small scale laboratory experiments, especially on rock fracture behavior, and exchanges of test data among the funding organizations.

The achievements and lessons learnt through this first DECOVALEX project led the funding organizations to decide on an extension to a second phase named

DECOVALEX II (with the original DECOVALEX project called DECOVALEX I), for the period 1996–1999. The success of the work continued, leading to the subsequent phases of DECOVALEX III (2000–2003), DECOVALEX–THMC (2004–2007), DECOVALEX–2011 (2008–2011) and DECOVALEX–2015 (2012–2015) at the time of writing this Chapter. Such continued research is a rare phenomenon in international research co-operations in the field of radioactive waste management or in geosciences in general. The main reasons for such a long-term research co-operation are:

1. the main research topics are important for performance and safety assessments of GDRW repositories;
2. the project takes an integrated research approach combining numerical modeling, small scale laboratory tests and larger scale in situ experiments in different host rocks to conduct the verification, validation and reliability assessments of the application of numerical methods and techniques in support of long-term predictive modeling required by the safety assessments;
3. the research topics of THM and THMC processes in rock fractures and continuum geological porous media over periods of 3–4 years per project phase have been suitable for educating Ph.D. students. Over 30 doctoral students have conducted research on the DECOVALEX project's problems and successfully obtained their Ph.D. degrees—many of whom continued on to work in the field of radioactive waste management or similar fields concerning energy and mass transport;
4. research results have been widely published in the form of journal and conference papers, technical reports, Ph.D. theses, and edited volumes; and finally and most importantly,
5. DECOVALEX project provides an international platform for supporting the funding organizations' own R&D programs in reasonable time intervals, from multidisciplinary points of view, and from different countries with different backgrounds and emphasis.

2 PROJECT ORGANIZATION AND RESEARCH MANAGEMENT

Figure 2 illustrates the organization of the DECOVALEX I project, which started with DECOVALEX I and has continued, with only minor changes, up to the present

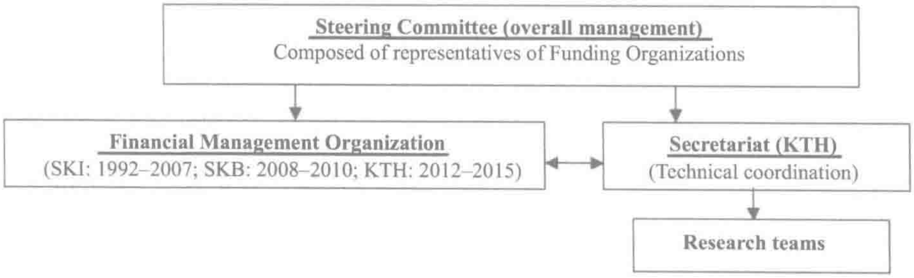

Figure 2 Organization structure of the DECOVALEX Project.

day. The Steering Committee is composed of one representative from each funding organization, and has the overall role of deciding project aims, content, tasks, duration, reporting/publications and the finances. The financial managing organization is responsible for managing the project economy, mainly issues of budget and expenditures. The Secretariat is responsible for administrative and technical management of the project, including arrangements of meetings, task coordination, communications, publications, reporting, and archives. The full names and the acronyms of the funding organizations and research teams from 1992 to the present day are listed in Tables 1 and 2. (Note that the participants in the planned 2016–2019 DECOVALEX phase are not included here because the arrangements for this phase are in the process of being developed as this Chapter is being written in 2015—but can be found at www.DECOVALEX.org). See Table 1 for the acronyms of the funding organizations, where letter 'D' indicates 'DECOVALEX', and research teams in Table 2.

For each DECOVALEX phase, the funding organizations propose tasks that are of importance to their respective R&D program. The final selection of tasks to be studied is decided by the Steering Committee through discussion and voting. The finally selected proposals are then further developed, including definition of objectives, coupled THM or THMC processes involved, input data (initial and boundary conditions, material properties), output specification requirements and time schedule. Usually, one problem is studied by several research teams sponsored by different funding organizations from different countries, with different modeling approaches, tools and different understanding of the physics involved—which is the key advantage that motivated continuation of the DECOVALEX project phases. Cycles of blind predictions followed by model calibrations with measured data, if available, have been the main approach to evaluate scientific quality and reliability of the results.

The selected proposals are classified as a Test Case (TC) or a Benchmark-Test (BMT) problem. The BMTs are mostly problems without (or with limited) data support from laboratory or in situ experiments. However, they can identify the need to establish more comprehensive conceptual understanding or key relevant parameters on coupled THM or THMC processes in porous fractured or continuum media in specific geological conditions, *e.g.* issues of complex fracture network geometry, upscaling and homogenization, special effects of certain physical processes such as heat advection by groundwater in fractures, impacts of glaciation and deglaciation cycles over long periods of time, etc. The TCs are defined based on lab or in situ experiments with measured data for testing, verifying, validating and supporting the development of constitutive models and computer codes applied. Often this helps to establish their shortcomings for further development to improve their capability for predictive modeling.

Both categories, BTMs and TCs, are necessary for planning, developing, validating and confidence building of numerical modeling techniques and are useful not only for GDRW repositories, but also for all fields involving energy and mass transport in geological systems. We use the term 'verifying' to relate to the process of comparing the computer modeling output of different teams, and 'validating' to compare the modeling output with measured lab and/or in situ data.

Table 1 Funding organizations for the DECOVALEX project (1992–2015).

Funding Organization	*Acronym*	*Country*	*Phases participated*
National Agency for Radioactive Waste Management	ANDRA	France	DI, DII, DIII
Atomic Energy Commission	CEA	France	DI, DIII
Institute for Nuclear Protection and Safety	IRSN/IPSN	France	DI–D2015
Atomic Energy of Canada Ltd.	AECL	Canada	DI
Ontario Hydro Co.	OH	Canada	DII
Ontario Power Generation Co.	OPG	Canada	DIII
Nuclear Waste Management Organization (former OPG)	NWMO	Canada	D-THMC
Atomic Energy Control Board/ Canadian Nuclear Safety Commission	AECB/CNSC	Canada	DI, DII, DIII, D-THMC
Radioactive Waste Repository Authority	RAWRA	Czech	D-2011, D-2015
Chinese Academy of Sciences, Institute of Rock and Soil Mechanics	CAS	China	D-THMC, D-2011, D-2015
Wuhan University	WHU	China	D-2011
European Commission (through the BENCHPAR project)	EU		DIII
Federal Institute for Geoscience and Natural Resources	BGR	Germany	DIII, D-THMC, D-2015
Helmholtz Centre for Environmental Research	UFZ	Germany	D-2015
Power Reactor and Nuclear Fuel Development Co.	PNC	Japan	DI
Japan Nuclear Cycle Development Institute (former PNC)	JNC	Japan	DII, DIII,
Japan Atomic Energy Agency (former JNC)	JAEA	Japan	D-THMC, D-2011, D-2015
Korean Atomic Energy Research Institute	KAERI	Korea (Republic of)	D-2011
Empresa Nacional de Residuos Radioactivos, S. A.	ENRESA	Spain	DII, DIII
United Kingdom Nirex Ltd.	NIREX	UK	DI, DII, DIII
Nuclear Decommissioning Authority	NDA	UK	D-2011, D-2015
Radioactive Waste Management	RWM	UK	D-2015
Environmental Agency	EA	UK	DII
Nuclear Regulatory Commission	NRC	USA	DI, DIII, D-2015
Department of Energy	DOE	USA	DIII, D-THMC, D-2015
Swedish Nuclear Fuel and Waste Management Co., Sweden	SKB	Sweden	DI, DII, DIII, D-THMC, D-2011
Swedish Nuclear Power Inspectorate, Sweden	SKI	Sweden	DI, DII, DIII, D-THMC
Centre for Radiation and Nuclear Safety	STUK	Finland	DI, DII, DIII, D-THMC
Posiva Oy	POSIVA	Finland	D-2011
Swiss Federal Nuclear Safety Inspectorate	ENSI	Switzerland	D-2015