Modelling Rock Fracturing Processes

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A Fracture Mechanics Approach Using
FRACOD

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Cover illustration: This figure shows a typical case of hydraulic fracturing simulated using FRACOD. A borehole is drilled in a rock mass with several isolated pre-existing fractures. A high fluid pressure is then applied in the borehole which causes fracture initiation at the borehole wall, followed by fracture propagation toward the pre-existing fractures. The hydraulically driven fractures eventually coalesce with the pre-existing fractures. The pre-existing fractures then propagate under the influence of high fluid pressure. The figure is a plot of vertical displacement contour in the vicinity of the injection hole and the new and pre-existing fractures. Figure created by the authors.

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Foreword

This carefully written and expert text on fracturing of rock, reflecting deep theoretical understanding and second to none modelling abilities, has been written by three well-known authors. They combine theoretical brilliance and creativity, a long life of expert insight, professorship, and authorship in many rock mechanics problems, and expert application in several current nuclear waste repository studies. All three are well known to the reviewer, who has been persuaded to provide an opinion on this interesting text, despite an altogether simpler background in practical rock engineering. Their theoretical and applied fracture mechanics text, which of course is written for experts, is presented in such an ordered manner that it is digestible, even if the theory and extensive matrices required have to be accepted as the production of an unusually talented main author, whose exceptional mathematical abilities have never been in doubt.

The usefulness of FRACOD, the boundary element – displacement discontinuity method (DDM) of modelling of fracturing in over-stressed rock, which is developed, validated, and demonstrated during the 200 pages of this book, has several times been appreciated by the reviewer, in specific deep tunnelling and over-stressed shallow cavern scenarios in the past 7 or 8 years. In the first case, the predicted deeply penetrating stress-induced rock-bursting damage, with and without additional jointing, caused by in situ principal stresses as high as 60 MPa, was not believed by the contractor, but was severe enough to later damage the TBM, and required completion of the tunnel by drill-and-blast, an approach suggested many years before completion, due to the severe FRACOD-related results. In the second case, the predicted fracturing of weather-weakened rock beneath the elephant-footing foundations of overloaded lattice girders was observed in practice (due to post-collapse excavation), and was undoubtedly a triggering factor in the collapse of the large cavern at shallow depth, with the severe overloading due to an undiscovered ridge of rock high above the cavern arch. Various load, rock strength, and modulus variations were tested, and the modelled results could be ‘seen’ in practice, at the overloaded side of the cavern.

Chapters 2 and 3 of this book on the modelling of rock fracturing processes, lay a foundation for a thorough understanding of fracture mechanics, and its modelling

using DDM. Fracture initiation, and development with time, including sub-critical crack growth, and sliding on pre-existing joints is modelled by FRACOD. Coupled thermo-mechanical effects, coupled hydro-mechanical effects, and a particularly realistic looking hydraulic fracturing development in a (2D) rock mass with some pre-existing jointing, follow in later chapters, but are preceded by their theoretical description and possibility of development in FRACOD.

The authors have taken care to explain and then give examples of the input data needed for FRACOD and describe how it can be obtained from laboratory testing. They then validate FRACOD by comparing the numerical solutions, using a range of element sizes, with problems that have analytical solutions. This is done of course for tensile fracturing and shear fracturing, followed by modelling of creep (in the form of sub-critical crack growth), and ends with the coupled processes caused by heating or fluid pressure, and the different styles of fracturing they induce. The hydraulic fracturing development causes some wing cracks to form at the tips of the closest pre-existing jointing, on either side of the injection borehole.

The final chapter gives numerous cases of application of FRACOD, where the major emphasis is probably on the field of high-level nuclear waste isolation and also geothermal energy access boreholes. Particular concern is with the excavation disturbed zone, or EDZ, which can have important consequences both for well stability and for repository construction. The latter may be in different orientations with respect to, e.g., the major horizontal stress, where optimal disposal tunnel orientation may not be optimal for access tunnel excavation. Subsequent canister placement in large diameter holes and the subsequent thermal loading phase have been tested at large scale by Sweden's SKB in Äspö, and here these have been modelled with FRACOD.

For those who desire greater insight and understanding of fracture mechanics, coupled process modelling, and the application and capabilities of the code FRACOD, this book is of course 'a must have' item. It is an impressive accomplishment, and congratulations to all the authors for their unique and essential contributions to its success.

Oslo, Norway
August 2012

Nick Barton

Preface

This book describes a unique approach using the principles of rock fracture mechanics to investigate the behaviour of fractured rock masses for rock engineering purposes.

Rock fracture mechanics, a promising outgrowth of rock mechanics and fracture mechanics, has developed rapidly in recent years, driven by the need for in-depth understanding of rock mass failure processes in both fundamental research and rock engineering designs.

Today, as rock engineering extends into many more challenging fields (like mining at depth, radioactive waste disposal, geothermal energy, and deep and large underground spaces), it requires knowledge of rock masses, complex coupled thermal–hydraulic–chemical–mechanical processes. Rock fracture mechanics play a crucial role in these complex coupled processes simply because rock fractures are the principal carrier and common interface.

To date, the demand for rock fracture mechanics–based design tools has outstripped the very limited number of numerical tools available. Most of those tools were developed for civil engineering and material sciences and deal with substances such as steel, ceramic, glass, ice, and concrete which differ markedly from rocks in their fracturing behaviour.

To address this need, in 1990 the authors began the work of developing a practical numerical approach using fracture mechanics principles to predict rock mass failure processes. It started with a Ph.D. thesis by the first author suggesting a new fracture criterion that predicts both tensile and shear fracture propagations, overcoming the shortcomings of traditional fracture criteria that predict only tensile failure. This approach has proved very effective in simulating the behaviour of multiple fractures in rock-like materials in laboratory tests.

The development of this modelling approach with a view to engineering application was initially driven by proposals for radioactive waste disposal in Sweden and Finland, where fracture propagation in the hard bedrock (due to thermal loading and glaciations) is considered a major risk factor. During this period, an earlier version of the code FRACOD was developed, capable of simulating fracture propagation, fracture initiation, and acoustic emission. This code capability was then expanded to

include time-dependent rock behaviour and subcritical crack growth through a Ph.D. study in 2008 by the third author. In the course of this development process, many application case studies were conducted using FRACOD, including the well-known Äspö Hard Rock Laboratory's Pillar Spalling Experiments (APSE) in Sweden, the DECOVALEX International Collaboration Project, and the Mizunami Underground Research Laboratory (MIU) Investigations in Japan.

This fracture mechanics approach was further expanded to other application fields of rock engineering such as tunnelling and geothermal energy. In an attempt to investigate the stability of a tunnel under high horizontal stresses, FRACOD successfully predicted the same "log-spiral" type of fracturing pattern around the tunnel that was observed in the laboratory (Barton 2007). When applied to back-analysis of in situ stresses in a 4.4 km deep geothermal well in Australia, this approach was shown to realistically simulate the borehole breakout, thereby accurately predicting the rock mass stress state.

Recent surges in fossil fuel (e.g., oil and coal) prices and concerns about global warming have significantly increased worldwide interest in alternative energy sources and storage methods. Thus, accurate prediction of the coupled behaviour of rock fracturing, fluid flow and thermal processes is now a vital scientific endeavour. FRACOD seeks to address the complex design issues facing various emerging developments in energy-related industries including geothermal energy, LNG underground storage, and CO₂ geosequestration.

Since 2007, the focus of FRACOD development has shifted to the coupling between rock fracturing, fluid flow, and thermal loading thanks to the establishment of an international collaboration project with participants from Australia, Europe, and South Korea. Coupling functions of T-M (thermal-mechanical) processes and H-M (hydro-mechanical) processes have been developed in FRACOD. Several application case studies related to hydraulic fracturing and LNG underground storage have been conducted.

Development and application of the fracture mechanics approach using FRACOD has not stopped – and it will continue. Currently, the full three-way coupling of M-T-H is being developed in the two-dimensional FRACOD code to address industry needs. A three-dimensional version of FRACOD is also under development for modelling true 3D problems.

It is our wish that this book will familiarize readers with the concepts and basic principles of using a fracture mechanics approach to solve rock engineering problems. We also hope this book will stimulate more research and development in this area, eventually providing the rock mechanics and rock engineering society with an alternative, robust, and unique tool for rock engineering design.

Brisbane
July 2012

Acknowledgements

The development and first rock engineering applications of FRACOD 2D can be traced back to 1992 when the first and second authors started up the activities at the Division of Engineering Geology of the Royal Institute of Technology, KTH, in Stockholm, Sweden. Sometime later, the third author, Mikael Rinne, joined the group at KTH and added to the further development of the code. We gratefully acknowledge the encouragement and support provided by KTH during the period 1992–2001.

The first applications of the code to rock engineering problems were done in close co-operation with the Swedish Nuclear Power Inspectorate, SKI, in Stockholm. The code was applied to stability problems of tunnels and deposition holes of the early versions of the KBS-3 system for disposal of spent nuclear fuel. We are thankful to Dr. Johan Andersson and Dr. Fritz Kautsky at SKI for providing challenging problems and stimulating discussions and SKI for the support of the code development.

The international contact network in the field of management of spent nuclear fuel led us to a close co-operation with Hazama Corporation in Japan. We are grateful to Hazama for the many years of support for developing the code and to Dr. Kiyoshi Amemiyia for supporting new developments of FRACOD to interesting nuclear waste handling problems in Japan. We would also like to thank Christer Svemar and Rolf Christiansson at the Swedish Nuclear Fuel and Waste Management Company, SKB, Stockholm for stimulating discussions and project support.

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Since 2004, several studies were conducted using FRACOD for geothermal energy development in Australia and they were supported by Geodynamics Ltd, Green Rock Energy Ltd, and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). We are very grateful for the support and close involvement in these studies by Dr. Doone Wyborn of Geodynamics Ltd, Adrian Larking and Gary Meyer of Green Rock Energy Ltd, and Dr. Rob Jeffrey of CSIRO.

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Since 2007, two international collaboration projects were established to develop an advanced numerical package based on FRACOD that predicts the effect of coupled explicit fracturing/fluid flow/thermal processes. The projects were led and supported by CSIRO Earth Science and Resource Engineering, Australia, and several international organisations participated in them. We are thankful to the following participants of the project and their organisations: Drs. Hyung Mok Kim and Eui Seob Park, Korea Institute of Geoscience and Mineral Resources; Drs. Taek Kon Kim, Jin Moo Lee, Hee Suk Lee, Tae Young Ko, and Julie Kim, SK Engineering and Construction, South Korea; Drs. Manfred Wutke, Ralf Junker, and Christian Bönnehan, Leibniz Institute for Applied Geophysics, Hannover, Germany; Drs. Tobias Backers and Tobias Meier, geomecon GmbH, Potsdam, Germany; Topias Siren and Matti Hakala, Posiva Oy, Finland; Dr. Doone Wyborn, Geodynamics Ltd, Australia; Prof. Ki-Bok Min, National University of Seoul, South Korea; Prof. Simon Loew, Federal Institute of Technology ETH Zurich, Switzerland.

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