Baotang Shen
Ove Stephansson
Mikael Rinne

Modelling Rock Fracturing Processes

A Fracture Mechanics Approach Using FRACOD

EXTRA MATERIALS
extras.springer.com

Springer

Baotang Shen • Ove Stephansson • Mikael Rinne

Modelling Rock Fracturing Processes

A Fracture Mechanics Approach Using FRACOD

Springer

Baotang Shen
CSIRO Earth Science and Resource Engineering
Brisbane, QLD, Australia

Ove Stephansson
Helmholtz Centre Potsdam
GFZ German Research Centre for Geosciences
Potsdam, Germany

Mikael Rinne
School of Engineering
Department of Civil and Environmental Engineering, Geoengineering
Aalto University
Espoo, Finland

Additional material can be downloaded from http://extras.springer.com

ISBN 978-94-007-6903-8 ISBN 978-94-007-6904-5 (eBook)
DOI 10.1007/978-94-007-6904-5
Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2013944753

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.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Modelling Rock Fracturing Processes

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 CO_2 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 Amemyia 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.

During the last two decades The Finnish Funding Agency for Technology and Innovation, TEKES, has supported the code development through funding the FRACOD code owner FRACOM Oy in Finland. We gratefully acknowledge the support by TEKES and our contact persons Lasse Pöyhönen and Arto Kotipelto. Support from the Finnish nuclear waste management company, Posiva Oy, in many phases of the code development is also highly appreciated. Special thanks go to Juhani Vira, Kimmo Kemppainen, and Topias Siren at Posiva.

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.

We would like to express our most sincere appreciation to Dr. Nick Barton who, over many years, has been one of the strongest advocators of FRACOD development. With his strong support and guidance, FRACOD has continued its improvement, in particular for applications to underground tunneling.

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 Bönneman, 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.

The later development in FRACOD and the writing of this book could not have been possible without the strong support from CSIRO Earth Science and Resource Engineering, Australia. We would like to thank Dr. Hua Guo for his strong support and scientific contribution to the international collaboration projects. We are very grateful to Dr. Binzhong Zhou for the development of the pre- and postprocessors to FRACOD, Dr. Jingyu Shi for the development of the first parts of the three-dimensional version of the code.

The second author is thankful to Dr. Reinhard Hüttle, Prof. Georg Dresen, and Dr. Gottfried Grünthal of GFZ German Research Centre for Geosciences, Potsdam, Germany, for providing a stimulating environment and for supporting this work. The FRACOD code needs elastic input parameters, rock fracture mechanics, and thermal data. For providing all this, we appreciate the close co-operation of Dr. Tobias Backers at geomecon GmbH (previously GeoFrames GmbH) which has been of value in the development of FRACOD.

The third author wishes to thank Helsinki University of Technology, which is today part of the Aalto University in Finland. Special thanks go to Prof. Pekka Särkkä and his laboratory personnel at Aalto. Rock testing to verify the new features in the code has been an essential part in the code development.

We very much appreciate the expertise and skill of Andreas Hendrich, GFZ, who, with great patience, redrew all the viewgraphs. Also, we like to thank Jeoung Seok Yoon, Section 2.6, GFZ, for his useful comments to the manuscript from a Postdoc's point of view. The English editing of the final version of the manuscript was done by Michelle Burgess and she is gratefully acknowledged. Finally, we acknowledge the support by Petra D. Van Steenbergen and Hermine Vloemans, Springer, SBM NL, for their help with the publishing of this book.

Finally, we would like to thank our families for the patience and support in completing this book.

Contents

Chapter 1
Introduction

Abstract Understanding the long-term behaviour of a rock mass and the coupled hydro-thermal-mechanical processes is crucial for geological radioactive waste disposal, geothermal, mining, LNG underground storage, and CO_2 geosequestration. Rock fracture initiation and propagation are the key mechanism for rock mass instability.

The ability to predict and realistically reproduce rock mass behaviour using a numerical model is a pivotal step in solving many rock engineering problems. Although several existing numerical codes can model the behaviour of jointed or fractured rock mass, most do not consider the explicit fracture initiation and propagation—a dominant mechanism, particularly in hard rocks.

The *FRA*cture propagation *COD*e (FRACOD) presented here is a two-dimensional computer code designed to simulate fracture initiation and propagation in elastic and isotropic rock mediums. This book focuses on the theories and numerical principles behind FRACOD, providing examples where the numerical method is applied to solve practical problems.

Rock mass is increasingly employed as the host medium for a vast array of human activities. Facilities like storage areas, wells, tunnels, underground power stations are located in a variety of rock types and under different rock mechanical conditions. Excavation stability is imperative for all such constructions, in both the short and long term.

Understanding the long-term behaviour of a rock mass is crucial for safety and performance assessments of geological radioactive waste disposal. Hydro-thermal-mechanical couplings of the ongoing processes around these repositories are particularly important. The understanding of fracturing of rock masses has also become a critical endeavour for energy extraction and storage. Small-scale breakouts around single wells in petroleum engineering can devastate the oil and gas extraction from source rock. The large-scale fracturing of rock formations for improved oil, gas and heat extraction is an essential field of development in the

B. Shen et al., *Modelling Rock Fracturing Processes: A Fracture Mechanics Approach Using FRACOD*, DOI 10.1007/978-94-007-6904-5_1,

petroleum and geothermal industries. CO_2 geosequestration is a complex new field of rock engineering where fracturing of the overburden rock during pressurization must be prevented while fracturing of the storage formation might be needed. All these intricate design tasks require powerful prediction and modelling tools.

Failure of brittle rock is often associated with a rapid and violent event, as detected in short-term loading strength laboratory tests. From these test results, the mechanical properties of rock including fracture mechanics parameters are obtained. When rock is stressed close to its short-term strength, slow crack growth (also called subcritical crack propagation), occurs. With time, this slow fracturing process may generate critical stress concentrations that lead to a sudden unstable failure event. Slow subcritical crack growth (SCG) is thought to play an important role in long-term rock stability at all scales and for all kinds of rocks, ranging from laboratory samples to earthquake-generated faults. When sudden rock movement occurs in nature or around excavations the consequences can be serious.

The ability to predict and realistically reproduce rock mass behaviour using a numerical model is a pivotal step in solving many rock engineering problems. Numerical modelling can improve our understanding of the complicated failure processes in rock and the many factors affecting the behaviour of fractured rock. When our models manage to better capture the fundamental failure mechanisms observed in the laboratory, our ability to generate reliable large-scale models improves, as does our ability to predict the short and long-term behaviour of rock masses in situ. Our ability to identify conditions where time is an important variable for the stability and long-term behaviour of rock excavations is likewise enhanced.

Several different types of numerical methods have been developed for various geomechanical problems (Jing 2003). Since every method and code has its advantages and disadvantages, the choice of a suitable code should be carefully assessed for each rock-engineering problem. Code suitability depends on the character of the problem and the goal of the study. The mechanical behaviour of the rock mass is largely influenced by the presence of natural discontinuities. Hence, numerical methods that allow the introduction of displacement discontinuities into the continuous medium are often required in solving rock engineering problems.

Numerical methods can be subdivided into "Continuum methods" and "Discontinuum methods". Continuum methods (or continuum approaches) do not take into account the presence of distinct discontinuities. If natural discontinuities are numerous, then the substitution, at a certain scale, of a discontinuous medium with a continuous one is required. The mechanical characteristics of the continuous medium must be such that its behaviour is equivalent from a mechanical point of view to that of the discontinuous medium. The effects of fractures are smoothed out and the heavily jointed rock mass is considered as an equivalent continuous medium.

The Discontinuum methods (or "Explicit joint approaches") allow one to incorporate discrete discontinuities in the displacement field, that is, individual joints in the rock mass can be modelled explicitly. Discontinuum methods may describe the fracture process using fracture mechanics principles.

Although several existing numerical codes can model the behaviour of jointed or fractured rock mass, most do not consider the explicit fracture initiation and propagation—a dominant mechanism, particularly in hard rocks. A very limited number of codes can model the fracture propagation but are not designed for application at engineering scales. Using fracture mechanics principles, this book aims to introduce unique numerical approaches to complex rock failure problems.

The *FRA*cture propagation *COD*e (FRACOD) presented here is a two-dimensional computer code designed to simulate fracture initiation and propagation in elastic and isotropic rock mediums. The code employs Displacement Discontinuity Method (DDM) principles and a fracture propagation criterion for detecting the possibility and path of fracture propagation, Shen and Stephansson (1993).

This book focuses on the theories and numerical principles behind FRACOD, providing examples where the numerical method is applied to solve practical problems involving rock fracture initiation and propagation in rock masses subjected to various loads (including in situ stress, thermal stress and hydraulic pressure).

We begin with the fundamental theory of fracture mechanics and the Displacement Discontinuity Method in Chaps. 2 and 3. In Chaps. 4, 5, 6, 7 and 8, we describe the methodology and principles of using FRACOD to simulate joint behaviour, time-dependency, multiple region systems, gravitational problems, and sequential excavations. In Chap. 9, the development of a thermal–mechanical coupling function in FRACOD is described. In Chap. 10, the newly developed hydro-mechanical coupling function is introduced. Chapter 11 presents the function for modelling anisotropic problems. Chapter 12 outlines the rock properties needed for modelling with FRACOD. Chapter 13 gives numerous verification cases of the code. Finally, Chap. 14 describes several real case studies, applying FRACOD to practical problems.

For those wishing to try the numerical code FRACOD, the demonstration version of FRACOD is provided and can be downloaded from http://extras.springer.com.

References

Jing L (2003) A review of techniques, advances and outstanding issues in numerical modelling for rock mechanics and rock engineering. Int J Rock Mech Min Sci 40:283–353

Shen B, Stephansson O (1993) Modification of the G-criterion of crack propagation in compression. Int J Eng Fract Mech 47(2):177–189