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Fundamentals of Discrete Element Methods for Rock Engineering

Theory and Applications

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To my parents and grandparents with the warmest memories
and
To my beloved wife, Wenli, and daughter, Fei-Fei

Lanru Jing

To my beloved wife Almut and Samuel & Naemi

Ove Stephansson

FOREWORD

In order to coherently design structures built on and in rock masses, some form of model is required so that the future can be predicted, e.g., what will happen if a tunnel with a certain size and shape is constructed at a given orientation and depth in a particular rock mass? For the prediction to be adequate, the model must represent the rock reality to a sufficient extent: the model should contain the necessary physical variables, mechanisms and associated parameters – and be able to simulate the perturbations introduced by engineering activities. We require a model that can accommodate the discontinuous, inhomogeneous, anisotropic and non-elastic behavior of rock masses. In particular, we must be able to model fractures in the rock and the consequential systems of rock blocks which rock masses comprise. For this reason, the subject of discrete element models is crucial to the success of rock engineering structures, all of which, in their different ways, are built to advance civilization.

Accordingly it is important to understand the material in this book because of the requirement that the distinct element models supporting the engineering design must be realistic, and one can audit a model's operation and output only if one understands its content, operation, the significance of the input parameter values and hence the output. Unlike many other engineering disciplines, in rock engineering we can rarely validate the model output, and so more effort has to be expended in ensuring that the computer model is well constructed in terms of the idiosyncrasies of rock masses.

We are fortunate, therefore, that the two authors, Lanru Jing and Ove Stephansson, have found time in their busy schedules to write this authoritative book. They are experts in the subject matter and have the necessary fundamental understanding of the rock mass geometry and mechanics supporting the discrete element codes. The book systematically explains each facet of the subject from first principles. Moreover the clarity with which the book has been written ensures that, on completion of the book, the conscientious reader should be able to share the authors' complete understanding of the subject matter.

As I progressively read the draft version of the book, the sequence of the subjects, the emphasis on ensuring physical laws being satisfied, the erudition, the lucid style and the ever-present precision of the explanations pulling the reader onwards, plus the fact that the overall modeling purpose is to predict the future, reminded me of the philosophy of Aristotle, student of Plato and tutor to Alexander the Great. Aristotle considered that objects had four causes: 'material,' from which an object is made; 'formal,' the pattern in which the material is assembled; 'efficient,' the agent or force creating the object; and 'final,' the purpose of the object. In our context, the 'material' cause is the host rock mass, the 'formal' cause is the rock engineering design based on modeling, the 'efficient' cause is the rock construction process and the 'final' cause is the operational engineering function. Aristotle thought that an explanation which includes all four causes completely captures the significance and reality of the object.

Additionally Aristotle thought that the pull of the future is more important than the push of the past because, in his teleological approach, the nature of an object is inextricably linked to its goal. With distinct element models, we are not building so much on earlier more idealized elastic continuum models but being pulled forward by the need to have new types of models that incorporate fractures more realistically. He also said that 'It is the mark of an instructed mind to be satisfied with that degree of precision that the nature of the subject admits, and not to seek exactness when only an approximation of the truth is possible' – which is an implicit recurring theme in the authors' explanations in this book.

Finally Aristotle considered that happiness is achieved by the use of our intellectual faculties and by practicing intellectual virtue. Thus I hope that all readers, through combining their own enhanced understanding of discrete element models with the overall goal of realistically characterizing rock masses and simulating the physical mechanisms, will be as happy as I am to have read the book from cover to cover.

Professor John A Hudson, *FREng*
Imperial College and Rock Engineering Consultants, UK
President of the International Society for Rock Mechanics (ISRM) 2007–2011

PREFACE

This book is a summary of our collaborative teaching and research efforts over the last two decades relating to the subject of discrete element methods (DEM) and its applications to rock mechanics and rock engineering. We have not intended this book to be a thorough presentation of the most current cutting-edge research subjects in the fields of DEM and its applications in geosciences and geoengineering – because the advances are occurring too rapidly. Instead we present some fundamental concepts behind the basic theories and tools of DEM, its historical development and its wide scope of applications in geology, geophysics and rock engineering. We hope that, with this moderate ambition, it may be more helpful and useful for a larger number of practicing engineers, students and researchers alike and serve as a starting platform for more advanced and in-depth further studies.

Unlike almost all books available on the general subject of DEM, this book includes coverage of both explicit and implicit DEM approaches, namely the distinct element methods and discontinuous deformation analysis (DDA) for both rigid and deformable blocks and particle systems, and also the discrete fracture network (DFN) approach for fluid flow simulations. Actually the latter is also a discrete approach of importance for rock mechanics and rock engineering. In addition, brief introductions to some alternative approaches are also provided, such as percolation theory and Cosserat micro-mechanics equivalence to particle systems, which often appear hand in hand with the DEM in the literature.

We provide a presentation of the fundamentals of the governing equations of the discrete systems concerning motion, deformation, fluid flow and heat transfer, to an extent that is currently considered in some available DEM codes. Special attention is given to constitutive models of rock fractures and fracture system characterization methods. These two issues are the basic building blocks of DEM and also have the most significant impacts on the performance and uncertainty of the DEM models.

The DEMs were pioneered and continuously developed by Dr P. A. Cundall, the creator of the distinct element methods, and Dr Genhua Shi, the creator of DDA, block theory and numerical manifold method. The authors learned DEM basics from them and received continuous inspirations and encouragements. This book presents only some basics of the distinct element methods and discontinuous deformation analysis, only small parts of their outstanding contributions.

The first author expresses his special gratitude to Professor Xuefu Yu in China, who led the author into the fields of rock mechanics and numerical modeling in late 1970s and provided continuous guidance and encouragements.

We would like to thank friends at Itasca Consulting Group Ltd, especially Dr R. D. Hart and Dr L. Lorig, for their continued support and kindness over the past decades.

We would especially like to thank our former and current doctoral students, especially F. Lanaro, K.-B. Min, T. Koyama and A. Baghbanan, who have contributed a great deal to some of the important results presented in this book and have helped with the graphics as well.

For the presentation of the explicit DEM methods (Chapter 8), we rely heavily on the codes of the Itasca Consulting Group Ltd, i.e., UDEC, 3DEC and PFC codes, due to the fact that these codes have represented the main stream of development and application of the explicit DEM approach since the early 1970s and much of our work has been developed using this approach and these codes. Extensive use of material from the manuals of the codes has therefore been inevitable. However, we have tried to focus on the fundamental concepts behind the algorithms and coding techniques as much as possible and to avoid specific code features. Additional material concerning the basics of DEM, which come from sources different from the Itasca codes or publications, has been inserted at appropriate places. We hope that, by including these, a more balanced presentation to the subject as a whole has been achieved.

The first author would like to thank Dr J. Harrison and Mrs M. Knox in the Rock Mechanics Group at Imperial College, London, and Prof. G. Dresen and Dr T. Backers at GFZ, Potsdam, Berlin, for their hospitality and help during his two sabbatical visits to their groups when writing parts of this book. Guidance, encouragement and fruitful discussions from Dr Genhua Shi, the creator of block theory and DDA, are especially appreciated.

The second author started working on the book during his sabbatical stay at the Department of Engineering Geology, Technical University of Berlin. The kind hospitality provided by Prof. J. Tiedemann and Drs M. Alber and D. Marioni is gratefully acknowledged.

The authors would like to express their most sincere gratitude especially to Prof. John A. Hudson for his considerable efforts in checking the English, correcting errors and commenting on technical contents throughout all chapters of this book in great detail and writing the Foreword. His contribution to this book is tremendous and much appreciated.

This book would not have been completed without the devoted love, understanding and support from our families.

Lanru Jing and Ove Stephansson
December 2006, Stockholm

CONTENTS

1 INTRODUCTION

This book is about the fundamentals and some application cases of the discrete element methods (DEM). The main reason for the general difficulties in modeling rock masses, by whatever numerical method, is that rock is a natural geological material and so its physical and engineering properties cannot be established or defined through a manufacturing process as for metals or plastic materials. The rock masses are largely DIANE (discontinuous, inhomogeneous, anisotropic and non-elastic) in nature (Harrison and Hudson, 2000). Rock masses are pre-loaded, i.e. they are under stress and continuously affected by dynamic movements in the upper crust of the Earth, such as tectonic movements, earthquakes, land uplifting/subsidence, glaciation cycles and tides, in addition to gravity. A rock mass is also a fractured porous medium containing fluids in either liquid or gas phase (e.g., water, oil, natural gases and air), under complex *in situ* conditions of stresses, temperature and fluid pressures. The combination of constituents and its long history of formation make rock masses complex materials for mathematical modeling in closed forms, and numerical modeling becomes inevitable for the design and performance assessments of rock engineering projects. Knowledge of the coupled thermo-hydro-mechanical and chemical (T-H-M-C) processes about evolutions of geometrical structures and constitutive behavior of the fractured rock masses under combined static/dynamic loading conditions, fluid flow and pressure, temperature gradients and geochemical reactions becomes essential for the reliable solutions of many rock engineering problems, especially when impacts on environment are required to be understood.

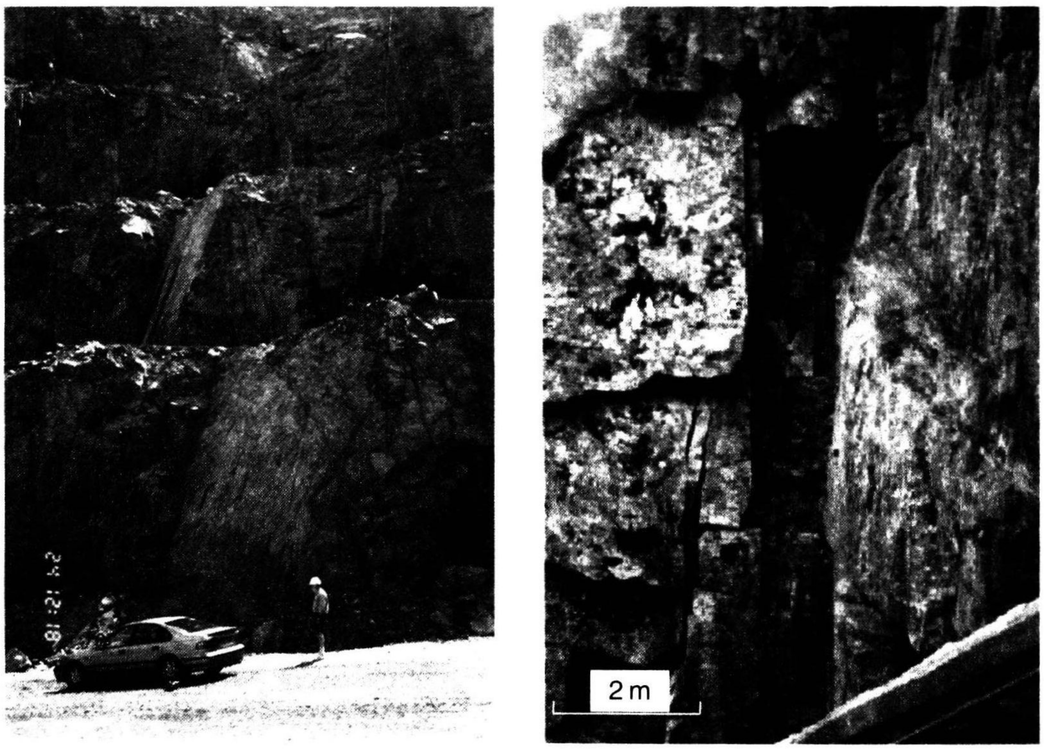
To adequately capture the complex physical and/or geochemical aspects of fractured rocks and the effects of perturbations introduced by engineering, a numerical method should have the capability to represent the system geometry (especially the fracture system geometry or its effects), boundary and initial conditions, the natural and induced loading/perturbation histories, adequate constitutive laws for both the rock matrix and fractures, including scale and time effects. For projects with environmental impacts, the necessary coupled physical and chemical process models must be considered, and the problems need to be represented essentially in three-dimensional (3D) space.

Such 'all-encompassing' numerical models do not exist today – mainly because of our limited knowledge concerning the physical behavior of rock fractures and fractured rock masses, our limited means to represent the geometry and evolution of complex rock fracture systems and our still limited computational capacity for large or very large scale problems, even given the perpetual increase of our computing capacity nowadays. For many practical problems with complex structural conditions, numerical modeling is still largely a tool for conceptual understanding, providing guiding ideas for design and operation of rock engineering structures where there is a large degree of uncertainty involved, and generic studies which can provide more in-depth understanding of the fundamental behavior of rock masses. However, for 'simpler' rock engineering projects, such as tunnel design and slope stability analysis in which there is adequate information about the behavior of rock materials and fractures, numerical modeling has already become a valuable and reliable design tool. The 'model' and the 'computer' are now integral components in rock mechanics and rock engineering. The numerical methods and computing techniques have become suitable and efficient tools for formulating and testing conceptual models and mathematical theories that can integrate diverse information about geology, physics, construction technique, economy and their interactions and, last but not the least, their impacts on the environment on one compact modeling and decision-making platform. This achievement has greatly enhanced the development of modern rock mechanics from the traditional 'empirical' art of rock strength estimation and support design towards the rationalism of modern continuum mechanics, governed by and established on the three basic principles of physics: mass, momentum and energy conservation with the necessary thermodynamic constraints.

1.1 Characteristics of Fractured Rock Masses

The rock masses in the Earth's crust consist of two major components: the intact rock matrix and discontinuities. The natural discontinuities include faults, joints, dykes, fracture zones, bedding planes and other types of weakness surfaces or interfaces, and these have a significant effect on the strength, deformability and permeability of fractured rock masses as a whole. The stability and service performance of rock engineering facilities, or the permeability of oil or geothermal reservoirs in fractured rock masses, are affected by the mechanical, thermal and hydraulic properties of these discontinuities, sometimes dramatically. It is the presence of these natural discontinuities that makes a fractured rock mass a complex material that behaves quite differently from its corresponding intact matrix.

Rock masses contain discontinuities of different sizes. Large-scale geological structures, such as faults, dykes or fracture zones, usually extend tens or hundreds of meters or even kilometers, in dimension, and typically have tectonic origins (e.g., faulting). They are usually manifested in engineering problems in limited numbers (Fig. 1.1). The discontinuities at microscopic scales (e.g., grain boundaries or micro-cracks) are distributed more randomly in rock matrices and in extremely large numbers, and their effect on the



(a) (b)

Fig. 1.1 (a) A fault intersecting an open-pit quarry slope in central England with observable trace length larger than 50 m; (b) a fracture zone in Tai-Shan, China, with trace lengths larger than 100 m.

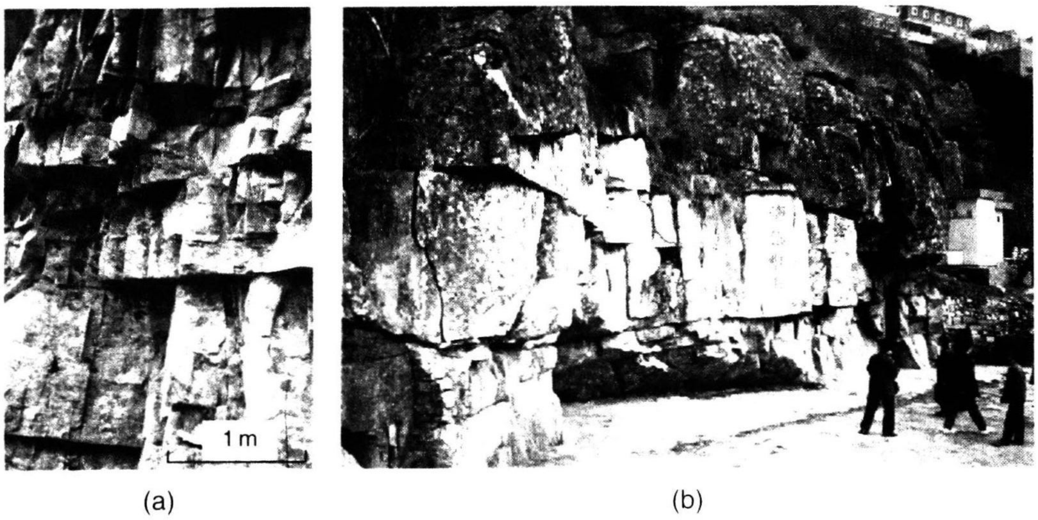


Fig. 1.2 Natural fracture systems as observed on a natural rock cliff (a) and on an excavated surface (b), with trace lengths up to about 30 m in Tai-Shan, China.

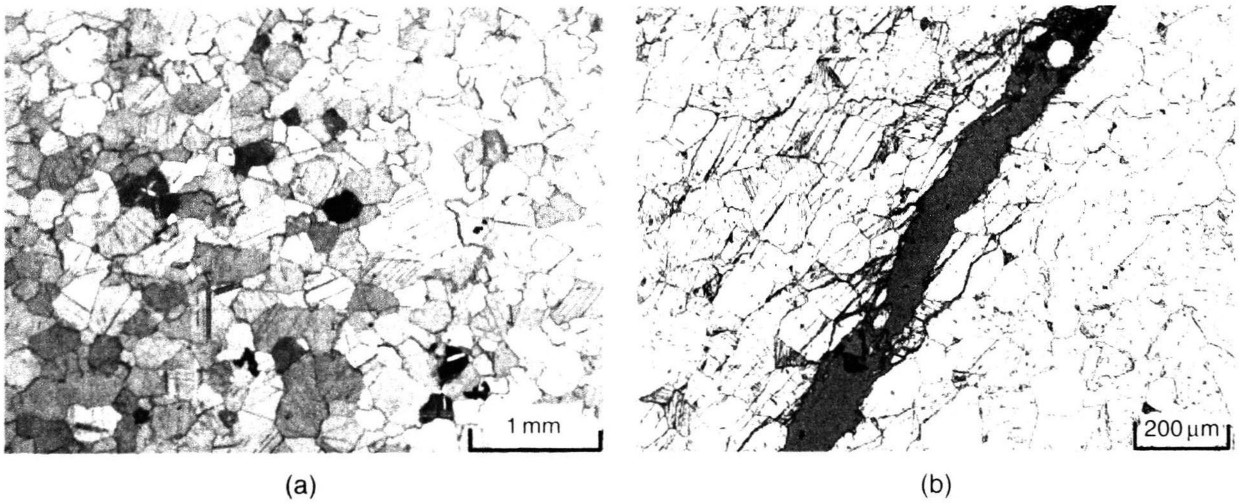


Fig. 1.3 Micrographs of a Carrara marble specimen (a) and a microcrack created during a fracture toughness test (b). Courtesy of Tobias Backer at GFZ, Germany.

behavior of intact rock is often assumed to be included in laboratory experimental results with samples of standard dimensions. The discontinuities whose dimensions lie between the above two extreme cases are usually joints, bedding planes, foliations or artificial cracks caused by engineering events such as blasting. Their linear sizes usually range from centimeters to tens of meters (Fig. 1.2). These discontinuities often appear in sets in terms of their clustered orientations. They often appear in large numbers in rocks and cut the rocks into blocks of complicated shapes. The presence of these sets of discontinuities makes the rock mass heterogeneous in configuration, highly discontinuous and non-linear in its behavior with respect to mechanical deformation and fluid flow. Due to their large numbers and complexities in geometry, their incorporation into numerical models is a challenging task. Figure 1.3 illustrates an example of the micro-structure of a marble specimen with varying grain sizes (Fig. 1.3a) and with an artificial microcrack (Fig. 1.3b).

The fractures present in rocks are not necessarily all natural features created by geological processes. They can also be created by human activities such as excavation and blasting, in both hard and soft rocks. Such fractures are the main ingredients of the so-called Excavation-induced Damage (or Disturbance) Zone (EDZ), which causes changes in the deformability and the pore structures and porosity (therefore permeability) in the rock matrix of an EDZ. Figure 1.4 below shows the excavation-induced fractures in a EDZ zone at an intersection of an old railway tunnel and an experimental drift at Tournemire, Southern

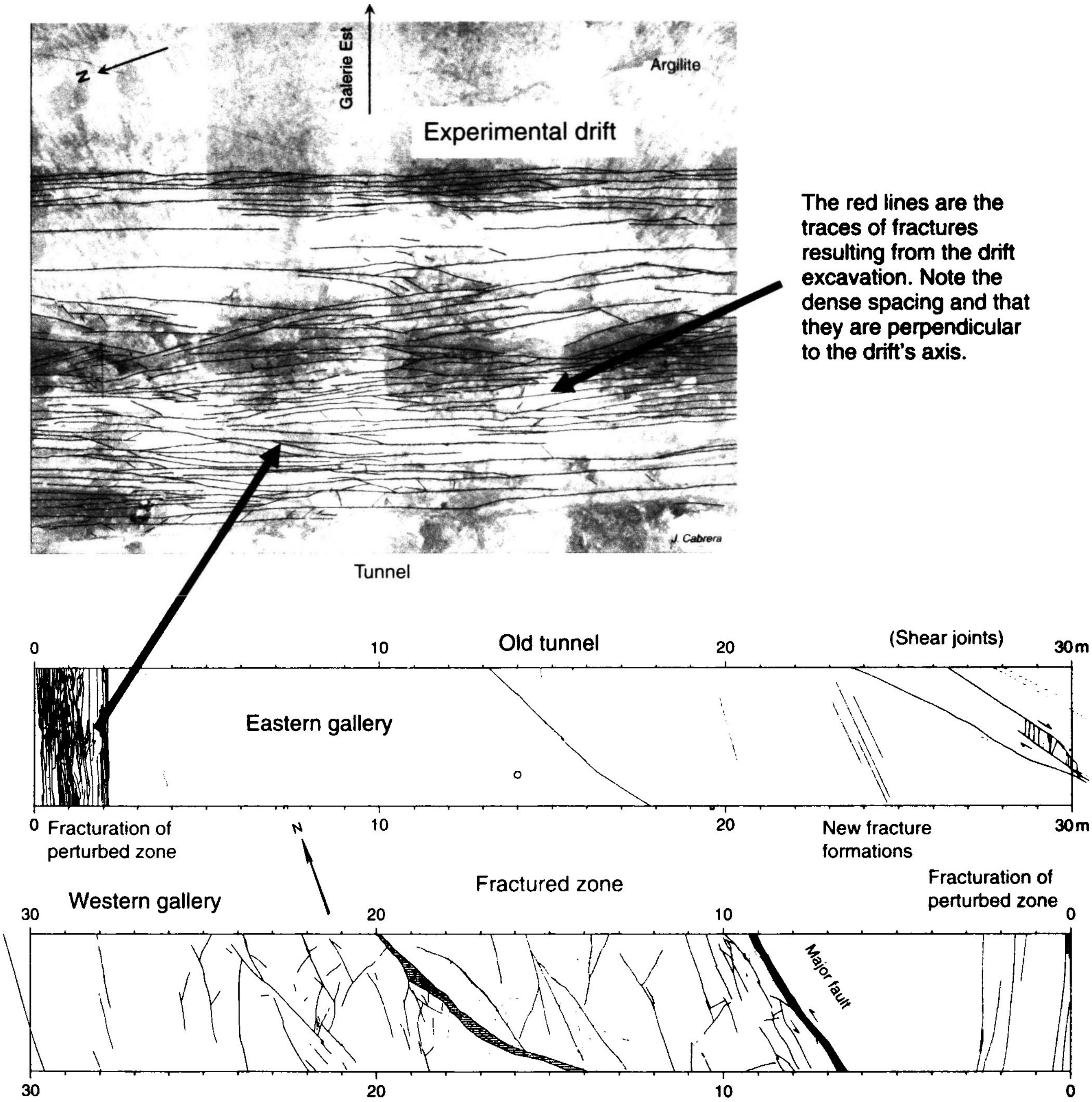


Fig. 1.4 Dense fractures created by the drift excavation at the intersection of a connection tunnel and an experimental drift at Tournemire experimental site, Southern France (Courtesy of Dr Amel Rejeb, IRSN, France).

France. Such artificially created dense fractures will have significant role in changing the coupled hydro-mechanical behavior and properties of this EDZ.

The terms 'discontinuity' and 'fracture' are used interchangeably in the rock mechanics literature for the same physical entity. The term 'fracture' is adopted throughout this book as a collective term for all types of natural or artificial discontinuities unless specifically stated otherwise. The surfaces of fractures may be simplified as nominally planar at the macroscopic level, but they may become wavy at larger scales with varying wavelengths and amplitudes. On close examination at the microscopic level, there exist numerous small-scale asperities on these surfaces. The presence of these asperities is the reason for the so-called roughness of the fracture surfaces and is the major factor causing complexities in the mechanical and hydraulic behavior of the rock fractures.