# Fundamentals of Discrete Element Methods for Rock Engineering

**Theory and Applications** 

### Lanru Jing

Group of Engineering Geology and Geophysics, Department of Land and Water Resources Engineering, Royal Institute of Technology, Stockholm, Sweden

### **Ove Stephansson**

Geo Forschungs Zentrum – Postdam, Department of Geodynamics, Postdam, Germany

## CONTENTS

Foreword	ix
Preface	xi
1. Introduction	. 1
1.1 Characteristics of Fractured Rock Masses	. 2
1.2 Mathematical Models for Discontinuous Media	. 7
1.3 Historical Notes on DEM	14
References	18
Part One: Fundamentals	23
2. Governing Equations for Motion and Deformation of Block Systems	
and Heat Transfer	25
2.1 Newton's Equations of Motion for Particles	26
2.2 Newton-Euler Equations of Motion for Rigid Bodies	27
2.3 Newton's Equations of Motion for Rigid Body Translations	29
2.4 Euler's Equations of Rotational Motion - the General and Special Forms	29
2.5 Euler's Equations of Rotational Motion – Angular Momentum Formulation	32
2.6 Cauchy's Equations of Motion for Deformable Bodies	34
2.7 Coupling of Rigid Body Motion and Deformation for Deformable Bodies	37
2.8 Equations for Heat Transfer and Coupled Thermo-Mechanical Processes	43
References	45
3. Constitutive Models of Rock Fractures and Rock Masses – the Basics	47
3.1 Mechanical Behavior of Rock Fractures	48
3.2 Shear Strength of Rock Fractures	50
3.3 Constitutive Models of Rock Fractures	55
3.4 Constitutive Models of Fractured Rock Masses as Equivalent Continua	67
3.5 Summary Remarks	94
References	103
4. Fluid Flow and Coupled Hydro-Mechanical Behavior of Rock Fractures	111
4.1 Governing Equations for Fluid Flow in Porous Continua	112
4.2 Equation of Fluid Flow Through Smooth Fractures	116
4.3 Empirical Models for Fluid Flow through Rough Fractures	120
4.4 Flow Equations of Connected Fracture Systems	126

5. The Design of Frantises System Characterization Field Manning and Stachastic	
Part Two: Fracture System Characterization and Block Model Construction	145
References	. 138
4.6 Remarks on Outstanding Issues	. 134
4.5 Coupling of Fluid Flow and Deformation of Fractures	. 128

#### The Basics of Fracture System Characterization -- Field Mappi na stocnastic

Simulations	147
5.1 Introduction	147
5.2 Field Mapping and Geometric Properties of Fractures	148
5.3 Statistical Distributions of the Fracture Geometry Parameters	161
5.4 Integrated Fracture System Characterization Under Site-Specific Conditions	171
References	173
6. The Basics of Combinatorial Topology for Block System Representation	179
6.1 Surfaces and Homeomorphism	181
6.2 The Polyhedron and its Characteristics	182
6.3 Simplex and Complex	184
6.4 Planar Schema of Polyhedra	190
6.5 Data Sets for Boundary Representation of Polyhedra	195
6.6 Block Tracing Using Boundary Operators	196
References	197
7. Numerical Techniques for Block System Construction	199
7.1 Introduction	199
7.2 Block System Construction in 2D Using a Boundary Operator Approach	201
7.3 Block System Construction in 3D Using the Boundary Operator Approach	214
7.4 Summary Remarks	228
References	231
Part Three: DEM Approaches	233
8. Explicit Discrete Element Method for Block Systems – The Distinct	
Element Method	235
8.1 Introduction	235
8.2 Finite Difference Approximations to Derivatives	237

- 8.3 Dynamic and Static Relaxation Techniques ...... 240 8.4 Dynamic Relaxation Method for Stress Analysis of Deformable Continua...... 254
- 8.5 Representation of Block Geometry and Internal Discretization ...... 257

xiv

8.6 Strain and Stress Calculations for the Internal Elements	268
8.7 Representation of Block Contacts	270
8.8 Numerical Integration of the Equations of Motion	271
8.9 Contact Types and Detection in the Distinct Element Method	275
8.10 Damping	280
8.11 Linked-list Data Structure	282
8.12 Coupled Thermo-Hydro-Mechanical Analysis	286
8.13 Hybrid DEM-FEM/BEM Formulations	301
8.14 An Example of Comparative Modeling Using FEM and DEM	302
8.15 Summary Remarks	303
References	306
9. Implicit Discrete Element Method for Block Systems – Discontinuous Deformation Analys	is
(DDA)	317
9.1 Energy Minimization and Global Equilibrium Equations	318
9.2 Contact Types and Detection	320
9.3 The Rigid Block Formulation	324
9.4 Deformable Blocks with a FEM Mesh of Triangular Elements	327
9.5 Deformable Blocks with a FEM Mesh of Quadrilateral Elements	330
9.6 Evaluation of Element Stiffness Matrices and Load Vectors	334
9.7 Assembly of the Global Equations of Motion	352
9.8 Fluid Flow and Coupled Hydro-mechanical Analysis in DDA	353
9.9 Summary Remarks	360
References	361
10. Discrete Fracture Network (DFN) Method	365
10.1 Introduction	365
10.2 Representation of Fracture Networks	367
10.3 Solution for the Flow Fields within Fractures	370
10.4 Alternative Techniques – Percolation Theory	381
10.5 Alternative Techniques – Combinatorial Topology Theory	385
10.6 Summary Remarks	388
References	390
11. Discrete Element Methods for Granular Materials	399
11.1 Introduction	399
11.2 Basic DEM Calculation Features for Granular Materials	405
11.3 Demonstration Examples of the PFC Code Applications	408
11.4 Numerical Stability and Time Integration Issues	416

xv

11.6 Summary Remarks	434
References	436
Part Four: Application Studies	445
12. Case Studies of Discrete Element Method Applications in Geology, Geophysics	
and Rock Engineering	447
12.1 Introduction	447
12.2 Geologic Structures and Processes	448
12.3 Underground Civil Structures	466
12.4 Mine Structures	475
12.5 Radioactive Waste Disposal	486
12.6 Rock Reinforcement	497
12.7 Groundwater Flow and Geothermal Energy Extraction	498
12.8 Derivation of Equivalent Hydro-mechanical Properties of Fractured Rocks	502
References	524
Appendix: Derivation of Expressions for Stress and Stress Couple Tensors of Particle Systems as	
Equivalent Cosserat Continua	539
Index	543

xvi