
Contents

Part I Assessment of Fractured Porous Media

1 Aquifer-Analogue Approach	3
1.1 Occurrence of Fractured Rock Aquifers	5
1.2 Characterization of the Hydraulic Properties of Fractured Rock Aquifers	5
1.2.1 Fracture Characterization and Flow Processes in Individual Fractures	6
1.2.2 Flow Processes in Fracture Networks	7
1.2.3 Unsaturated Flow Processes in Fractured Systems	9
1.3 Aquifer Genesis Approaches for the Assessment of Hydraulic Characteristics of Geological Materials	10
1.3.1 Aquifer Sedimentology	10
1.3.2 Genesis of Fracture Networks	11
1.4 The Aquifer Analogue Approach for Fractured Porous Aquifers	11
1.4.1 Objectives	12
1.4.2 Concept	12
2 From Natural System to Numerical Model	15
2.1 Natural Fractured Porous Systems	16
2.2 Model Concepts in Fractured Porous Systems	24
2.3 Governing Equations of Flow and Transport in Porous Media	26
2.3.1 Representative Elementary Volume	27
2.3.2 Flow Processes	27
2.3.3 Transport Processes.....	30
2.4 The Discrete Model Concept	32
2.4.1 Parallel-Plate Concept	33
2.4.2 Generation of Fracture Structural Models – FRAC3D ..	35
2.4.3 Spatial and Temporal Discretization	42
2.4.4 Applied Numerical Model – MUFTE-UG	43

2.4.5	Summary	43
2.5	Implementation of the Multi-continuum Concept	44
2.5.1	Governing Equations	44
2.5.2	Types of Coupling	47
2.5.3	Exchange Formulation	47
2.5.4	Numerical Model	51
2.5.5	Determination of Equivalent Parameters	52
2.5.6	Characteristic Values	54
2.5.7	Summary	60
2.6	Summary	61

Part II Project Scale Studies

3	Core Scale	65
3.1	Sample Characterization	65
3.2	Experiments	67
3.2.1	Fracture Geometry Investigations	67
3.2.2	Hydraulic and Pneumatic Experiments	83
3.3	Interpretation	86
3.3.1	Effective Conductivities Obtained from Fracture Geometry Data	87
3.3.2	Permeabilities Obtained from Hydraulic and Pneumatic Tests	91
3.3.3	Comparison of Conductivities	97
3.4	Summary	101
4	Bench Scale	103
4.1	Preparation of Fracture Porous Bench Scale Samples	103
4.1.1	Recovery and Preparation of the Cylindrical Bench Scale Samples	104
4.1.2	Recovery and Preparation of the Block Samples	109
4.2	Flow and Transport Experiments Conducted on Laboratory Cylinders	127
4.2.1	Application and Method	127
4.2.2	Technical Details	129
4.2.3	Procedure	131
4.2.4	Flexibility of the MIOJ	134
4.2.5	Flow Experiments	138
4.2.6	Transport Experiments	140
4.2.7	Conclusions	141
4.3	Interpretation of Experiments Conducted on Laboratory Cylinders	142
4.3.1	Sensitivity Analysis	142

4.3.2	Comparison of Measured and Simulated Tracer-Breakthrough Curves	148
4.3.3	Determination of Equivalent Parameters	154
4.3.4	Multi-continuum Modeling: Methodology and Approach.....	158
4.4	Flow and Transport Experiments Conducted on Laboratory Blocks	174
4.4.1	Integral Measuring Configuration	174
4.4.2	Port-Port Measuring Configuration	179
4.5	Interpretation of Experiments Conducted on Laboratory Block	197
4.5.1	Interpretation of Flow and Transport Experiments Based on Apparent Parameters	197
4.5.2	Multi-continuum Modeling: Methodology and Approach	201
5	Field-Block Scale	209
5.1	Choice of the Field Block Location.....	210
5.1.1	Regional Positioning.....	210
5.1.2	Local Positioning	213
5.2	Preparing a Test Site on the Field-Block Scale.....	215
5.2.1	Excavating and Cutting	216
5.2.2	Sealing Process and Installations.....	219
5.3	Characterization of the Rock-Matrix and Fracture-System	223
5.3.1	Statistical Evaluation of Fracture Parameters.....	224
5.3.2	Determination of Rock-Matrix Properties	228
5.4	Geostatistical Analysis of the Fracture Lengths and Fracture Distances	235
5.4.1	Strategy	235
5.4.2	Geostatistical Analysis of the Side Walls	239
5.4.3	Discussion of the Results	246
5.5	Orientating Measurements at the Unsealed Field Block	253
5.5.1	Connectivity and Flow Tests	254
5.5.2	Electromagnetic Reflection Method	254
5.6	Flow and Transport Tests at the Sealed Field Block.....	257
5.6.1	Tracer Injection and Detection Techniques	258
5.6.2	Measurements at Marginal Boreholes	261
5.6.3	Measurements at Central Boreholes	269
5.6.4	Conclusions	276
5.7	Application of the Discrete Model on the Field-Block Scale ..	277
5.7.1	Deterministic Fracture Model for the South-east/East Area and Boundary Conditions	278
5.7.2	Two-Dimensional Case Study: Simulation 1	278
5.7.3	Two-Dimensional Case Study: Simulation 2	281
5.7.4	Comparing Measured and Numerical Results	286

5.8	Integral Transport Behavior on the Field-Block Scale	287
5.8.1	Model Area and Boundary Conditions	287
5.8.2	Aquifer Properties	289
5.8.3	One-Dimensional Case Study	290
5.8.4	Three-Dimensional Case Study	290
5.9	A Study Concerning Boundary Effects on the Field-Block Scale	293
5.9.1	Model Design	294
5.9.2	Material Properties	294
5.9.3	Flow Simulation	295
5.9.4	Transport Simulation	297
5.9.5	Conclusions	300

Part III Scale-Independent Approaches and Investigations

6	The Multi-shell Model - A Conceptual Model Approach	305
6.1	Model Principle	306
6.2	Developing the Model	308
6.3	Boundary Conditions	310
6.4	Comparison with One-Dimensional Flow Model	312
6.5	Calculation of the Tracer Breakthrough Curves	313
6.6	Experimental and Numerical Confirmation	315
6.7	Tracer Distribution in a Two-Dimensional and Three Dimensional Flow System	315
6.8	Application of Multi-shell Model to Investigate the Anisotropic Nature	319
6.9	Précis of the Development of the Multi-shell Model	320
7	The Sensitivity Coefficient Approach	323
7.1	General Considerations	323
7.1.1	Governing Equations	323
7.1.2	Governing Sensitivity Equation	324
7.2	Calculation of the Parameter Derivative $\partial u / \partial k$	324
7.2.1	Influence Coefficient Method	325
7.2.2	Sensitivity Equation Method	325
7.2.3	Adjoint-State Method	325
7.3	Performance of the Sensitivity Coefficient Approach	328
7.3.1	Numerical Implementation	328
7.3.2	Application of Analytical Solutions	332
7.4	Analysis of Sensitivity Coefficient Distributions	333
7.4.1	Some General Considerations	333
7.4.2	Sensitivity with Respect to Hydraulic Conductivity ..	334
7.4.3	Sensitivity with Respect to Storage	338

7.4.4 Sensitivity Distribution for Different Hydraulic Test Configurations	339
7.5 Summary	343
8 Diffusivity Measurements	347
8.1 Concept of the Diffusivity Approach	347
8.2 Inversion Approach	349
8.3 Application	351
8.4 Conclusions	356
9 Analysis of the Influence of Boundaries	357
9.1 Qualitative Analysis of the Boundary Influence	358
9.1.1 Model Set-Up	358
9.1.2 Analysis of the Breakthrough Curves	359
9.1.3 Analysis of Characteristic Parameters	363
9.2 Normalization of Tracer-Breakthrough Curves	365
9.2.1 Development of the Normalization Concept	365
9.2.2 Application to Heterogeneous Domains	369
9.3 Summary and Conclusions	374
10 A Multivariate Statistical Approach	375
10.1 A Multivariate Statistical Approach for Evaluating Experimental Results	376
10.1.1 Methodology	377
10.1.2 Database	377
10.1.3 Definition of Variables Characterizing Flow and Transport Processes	379
10.1.4 Reducing the Multidimensional Variable Space	380
10.1.5 Processing of Data	382
10.1.6 Classification of the Flow and Transport Data by Using k-Means Cluster Analysis	385
10.1.7 Results and Interpretation	385
10.1.8 Summary and Conclusions	387
10.2 Determination of Domain Properties and Verification of the Results	389
10.2.1 Determination of Permeabilities	389
10.2.2 Set-Up of the Numerical Model	394
10.2.3 Discussion of the Results	396
10.2.4 Conclusions	400
10.3 Cluster Analysis to Set Up a Conceptual Multi-continuum Model	400
10.3.1 The Discrete Model	401
10.3.2 Multi-continuum Model	407
10.3.3 Comparison of <i>Classical</i> and <i>New</i> Approach	413

XIV Contents

10.3.4 Upscaling of the Multi-continuum Model	415
10.3.5 Conclusions.....	419
References	421
Nomenclature	443