
Hard Rock Hydraulics

An Introduction to Modeling

Fernando Olavo Franciss



CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

Contents

<i>Preface</i>	ix
1 About modeling	1
<i>1.1 Introduction</i>	
1.1.1 Scope and level of this book	3
1.1.2 Modeling uncertainty	3
1.1.3 Reducing uncertainty	4
1.1.4 Practical examples	10
1.1.4.1 Example of the difficulty to detect karstic features	10
1.1.4.2 Example of the value of published information	10
1.1.4.3 Example of the consequences of not detecting minor geologic features	12
1.1.4.4 Example of anticipating future WT levels	12
1.1.4.5 Example of pumping-rates predictions	13
1.1.5 Concluding remarks	14
<i>Notes</i>	17
2 Fundamentals	18
<i>2.1 Introduction</i>	
<i>2.2 Basic concepts</i>	
2.2.1 Pseudo-continuity	18
2.2.2 Porosity and permeability	19
2.2.3 Volumetric and gravimetric relations	21
2.2.3.1 Homogeneous and isotropic systems	21
2.2.3.2 Homogeneous and anisotropic systems	22
2.2.3.3 Heterogeneous systems	24
2.2.4 Observation scales	24
2.2.5 Description at different scales	29
<i>2.3 Hydraulic variables</i>	
2.3.1 Scalars, vectors, and second-order tensors	29
2.3.2 Groundwater flow description	33
2.3.3 The specific discharge	33
2.3.4 The hydraulic gradient	35
2.3.5 The hydraulic conductivity	42

2.3.5.1	Introduction	42
2.3.5.2	Fractures and conduits	44
2.3.5.3	Pseudo-continuity and pervious fractures	46
2.3.5.4	Valid pseudo-continuity assumption	53
2.3.5.5	Erratic discontinuities	54
2.3.6	Assessment of the hydraulic conductivities	56
2.3.6.1	Introduction	56
2.3.6.2	Exploring at the “sample scale”: back to 1930	59
2.3.6.3	Exploring old Lugeon tests: 1958 to 1968	59
2.3.6.4	Exploring integral sampling: 1968 to 1978	66
2.3.6.5	Exploring inverse solution methods: 1978 to 1988	71
2.3.7	Governing equations of groundwater flow	78
2.3.7.1	Preliminaries	78
2.3.7.2	Energy conservation principle: Darcy’s law	79
2.3.7.3	Mass conservation principle: continuity equation	80
2.3.7.4	Boundary conditions	86
2.3.8	Addenda	90
2.3.8.1	Effective velocity and specific discharge	90
2.3.8.2	Hydrodynamic gradient	91
2.3.8.3	Hydraulic conductivity for a group of random fractures	92
2.3.8.4	Energy conservation principle	93
2.3.8.5	Mass conservation principle	94
<i>Notes</i>		96
<i>References</i>		97
3	Approximate solutions	98
3.1	<i>Overview</i>	98
3.2	<i>Differential operators</i>	99
3.3	<i>Uniqueness of solutions</i>	103
3.4	<i>Approximate errors</i>	104
3.5	<i>Approximation methods</i>	110
3.5.1	Preliminaries	110
3.5.2	Collocation method	111
3.5.3	Least squares method	116
3.5.4	Galerkin’s method	122
3.5.4.1	Orthogonality	122
3.5.4.2	Galerkin’s approach	124
3.5.4.3	“Weak” solutions	127
3.5.4.4	Variational notation	129
3.5.5	Time-dependent solutions	132
3.6	<i>Addenda</i>	138
3.6.1	Classes of second-order partial differential equations	138
3.6.2	Minimizing squared residuals	139
3.6.3	Minimizing squared residuals changed by differential operators	140
3.6.4	The concept of orthogonality	140
<i>Note</i>		141
<i>References</i>		141

4 Data analysis	142
4.1 <i>Introduction</i>	142
4.2 <i>Analyzing geological data</i>	142
4.3 <i>Analyzing hydrologic data</i>	142
4.4 <i>Analyzing flow rate data</i>	148
4.5 <i>Analyzing hydraulic conductivity data</i>	151
4.5.1 Meaning of the hydraulic conductivity	151
4.5.2 Mapping of eigenvalues and eigenvectors	156
4.5.3 Interpolation of eigenvalues and eigenvectors	160
4.6 <i>Analyzing hydraulic head data</i>	162
4.6.1 Traditional analysis	162
4.6.2 Integrated hydraulic head analysis	175
<i>Notes</i>	180
<i>References</i>	181
5 Finite differences	182
5.1 <i>Preliminaries</i>	182
5.2 <i>Modeling hydrogeological systems</i>	183
5.2.1 Concepts	183
5.2.2 Guidelines for conceptual models	184
5.3 <i>Finite difference basics</i>	186
5.3.1 Difference equations	186
5.3.2 Finite differences	186
5.3.3 Difference equations for steady-state systems	188
5.3.4 Difference equations for unsteady-state systems	191
5.3.5 Difference equations for boundary conditions	193
5.3.6 Simultaneous difference equations	194
5.3.6.1 Preliminaries	194
5.3.6.2 Gauss–Seidel iterative routine	194
5.3.6.3 Crank–Nicolson iterative routine	201
5.4 <i>Finite differences algorithms for hard rocks</i>	204
5.4.1 Preliminaries	204
5.4.2 Steady-state solutions	205
5.4.2.1 Dupuit’s approximation	205
5.4.2.2 3D algorithms	219
5.4.3 Transient solutions	241
<i>Notes</i>	242
<i>References</i>	242
6 Applications	243
6.1 <i>Preliminaries</i>	243
6.2 <i>Fracture interconnectivity</i>	243
6.2.1 Interconnection between reservoirs	243
6.2.2 Pollution bypassing a wide river	243
6.2.2.1 The problem	243

6.2.2.2	The anomalies	247
6.2.2.3	The scanned images pieces of evidence	248
6.2.2.4	The hydraulic properties of the megafractures net	249
6.2.2.5	What happens during heavy rains	254
6.2.2.6	The 3D model results	255
6.3	<i>Thermal waters without hot points</i>	260
6.3.1	Preliminaries	260
6.3.2	Abridged geologic data	263
6.3.3	Model premises	263
6.3.3.1	Generalities	263
6.3.3.2	Effective mean regional porosity	265
6.3.3.3	Permeability	267
6.3.3.4	The groundwater recharge discussion	268
6.3.3.5	Fundamentals of heat transport	269
6.3.4	Modeling results	271
6.3.4.1	Dimensions and parameters	271
6.3.4.2	The heat transfer processes	272
6.3.4.3	Modeling the thermalism gradual decay	274
<i>Notes</i>	279	
<i>Bibliography</i>		281
<i>Index</i>		285