

Contents

1	Introduction	1
2	Formation and Types of Natural Ice Masses	7
2.1	Sea Ice	8
2.2	Polar Ice Sheets	12
2.3	Polar Ice Shelves	16
2.4	Icebergs	17
	References	18
3	Properties and Mechanical Behaviour of Ice	21
3.1	Basic Properties of Ice	21
3.2	Microstructure of Ice	24
3.3	Ductile Behaviour of Polycrystalline Ice	29
3.3.1	Elastic Behaviour	33
3.3.2	Creep Behaviour	36
3.4	Brittle Behaviour of Polycrystalline Ice	44
3.4.1	Tensile Fracture	46
3.4.2	Compressive Fracture	49
3.5	Thermal Properties of Ice	53
	References	54
4	Sea Ice in Civil Engineering Applications	59
4.1	Elastic Interaction of Ice with a Rigid Wall	60
4.1.1	Interaction Problem Formulation	61
4.1.2	Finite-Element Solution of the Problem	67
4.1.3	Numerical Simulations	69
4.1.4	Approximate Analytical Solution	72
4.2	Interaction of Creeping Ice with a Structure	74
4.2.1	Rheological Models for Sea Ice	75
4.2.2	Creep Buckling of Floating Ice	81
4.2.3	Ice Plate Failure Due to Its Thermal Expansion	88

4.2.4	Plane Ice–Structure Interaction Problem	96
4.2.5	Interaction of Ice with Cylindrical Structures	104
4.3	Ice Floe Impact on an Engineering Structure	115
4.3.1	Fracture of Ice at a Structure Wall	117
4.3.2	Numerical Method	121
4.3.3	Simulations of Forces Exerted on a Structure	122
	References	127
5	Sea Ice in Geophysical Applications	131
5.1	Important Physical Mechanisms in Sea Ice	132
5.2	Sea-Ice Dynamics Equations	133
5.2.1	Mass Conservation Equations	135
5.2.2	Linear Momentum Equation	137
5.2.3	Thermal Balance Equation	139
5.2.4	Constitutive Models	140
5.3	Material Formulation of Sea-Ice Equations	143
5.4	Finite-Element Model	145
5.5	Finite-Element Numerical Simulations	149
5.6	Smoothed Particle Hydrodynamics Model	155
5.7	SPH Numerical Simulations	160
	References	164
6	Micro-mechanical Models for Polar Ice	167
6.1	Single Crystal Kinematics	171
6.2	Constitutive Laws for an Ice Crystal	173
6.2.1	Strain-Rate – Stress Formulation	175
6.2.2	Stress – Strain-Rate Formulation	177
6.3	Macroscopic Behaviour of an Ice Polycrystal	178
6.3.1	Uniform Stress Model	181
6.3.2	Uniform Strain Model	189
6.4	Dynamic Recrystallization Models	194
6.4.1	Stress – controlled Recrystallization	197
6.4.2	Strain-Rate – Controlled Recrystallization	201
6.4.3	Strain – Controlled Recrystallization	203
6.5	Numerical Simulations	205
	References	216
7	Phenomenological Constitutive Models for Polar Ice	219
7.1	Continuum Mechanics Preliminaries	220
7.2	General Orthotropic Constitutive Law	222
7.3	Reduced Orthotropic Flow Law	226
7.3.1	Simple Flow Simulations	231
7.3.2	Material Response Functions	233
7.3.3	Model Illustrations	237

7.4	Inverse Orthotropic Flow Law	240
7.4.1	General Strain-Rate-Stress Formulation	241
7.4.2	Reduced Flow Law	242
7.4.3	Simple Flow Simulations	246
7.5	Additive Forms of Constitutive Laws	249
7.5.1	Stress and Strain-Rate Formulations	250
7.5.2	Material Response Functions	253
7.5.3	Illustrations	257
7.6	Dynamic Recrystallization Model	259
7.6.1	Multiplicative Form of the Model	260
7.6.2	Flow Simulations with the Multiplicative Law	264
7.6.3	Additive Form of the Model	267
7.6.4	Flow Simulations with the Additive Law	269
	References	271
8	Polar Ice Sheet Flow Models	275
8.1	Plane Ice Sheet Flow	278
8.1.1	Flow Problem Formulation	278
8.1.2	Scaled Equations	282
8.1.3	Finite-Element Model	287
8.1.4	Numerical Flow Simulations	291
8.2	Radially-Symmetric Ice Sheet Flow	297
8.2.1	Flow Problem Formulation	297
8.2.2	Scaled Equations	300
8.2.3	Leading-Order Equations and Solutions	303
8.2.4	Numerical Ice Sheet Flow Simulations	308
	References	317
	Appendix A: Physical Parameters Relevant to Ice	321
	Appendix B: Tensor Representations for Constitutive Laws	323
	Author Index	327
	Subject Index	331