## **Table of Contents**

Part I Introduction, Conception and the Importance of Avalanche Research				
1	Introduction			
	1.1		ation	3
	1.2	Goals,	Methods and Structure	8
		1.2.1	Goals	8
		1.2.2	Methodology	9
		1.2.3	Structure	10
	1.3	Necess	sities for Avalanche Studies	14
		1.3.1	Snow Avalanche Hazards and Fatalities	15
		1.3.2	Debris and Mud Flows, Pyroclastic Flows and Lahars .	17
		1.3.3	International Scientific Activities	24
	1.4	A Hist	tory of Avalanche Research	26
		1.4.1	Early History	27
		1.4.2	Modern History	27
2	Gra	anular	Avalanches: Definition, Related Concepts	
	and		/iew	47
	2.1		Complexity of Granular Materials	47
	2.2	Applic	eations of Granular Flows	48
		2.2.1	Chemical Process Engineering	48
		2.2.2	Geophysical Flows	49
	2.3		ctive Properties of Granular Materials	49
		2.3.1	Single-phase and Multi-phase Flows	50
		2.3.2	Dilatancy	51
		2.3.3	Cohesion	53
		2.3.4	Lubrication	54
		2.3.5	Fluidisation	55
		2.3.6	Unlubricated Sliding	57
		2.3.7	Segregation, Inverse Grading and the Brazil Nut Effect	60
	2.4	Granu	ılar Avalanches	62
		2.4.1	Definition	62
		2.4.2	Pattern Formation by Granular Avalanches	65

## XVIII Table of Contents

	2.5	Snow Avalanche Regions, Formation and Dynamics 2.5.1 The Home of Natural Snow Avalanches 2.5.2 Topographic Conditions 2.5.3 Snowpack and Weather Conditions 2.5.4 Size and Speed of Snow Avalanches	72 72 73 74 76
	2.6	2.5.5 Avalanche Dynamics  Types of Granular Avalanches  2.6.1 Flow Avalanches  2.6.2 Powder Avalanches	77 79 79 80
	2.7	2.6.3 Landslides and Avalanches on other Planets.  Fundamentals of Granular Avalanches  2.7.1 Some Characteristics of Flow Avalanches  2.7.2 Stress Generating Mechanisms  2.7.3 Density Variations  2.7.4 Constitutive Relations	85 88 88 90 91 92
	2.8	2.7.5 The Size Effect. Survey on Avalanche Modelling. 2.8.1 A View on Some Classical Avalanche Models. 2.8.2 VOELLMY's Pioneering Work 2.8.3 Experimental Data 2.8.4 Necessity for a New Model	104
		A Continuum Mechanical Theory for Dense Avalanche Down Non-Trivial Topographies	s
	ding	Down Non-Trivial Topographies	
Slic	ding		115
Slic	A C	Down Non-Trivial Topographies  Continuum Mechanical Theory for Granular Avalanches	115 115
Slic	A C	Down Non-Trivial Topographies  Continuum Mechanical Theory for Granular Avalanches  General Introduction	115 115 117
Slic	A C 3.1 3.2 3.3	Continuum Mechanical Theory for Granular Avalanches General Introduction	115 115 117 123 123 125
Slic	A C 3.1 3.2	Continuum Mechanical Theory for Granular Avalanches General Introduction	115 117 123 123 125 130 131 133 135
Slic	A C 3.1 3.2 3.3	Continuum Mechanical Theory for Granular Avalanches General Introduction. The SH-Model, Reduced to its Essentials. Generalisations of the Original Theory. 3.3.1 Generalisation with Respect to the Coordinate System 3.3.2 Generalisation with Respect to the Basal Topography. A Three-Dimensional Granular Avalanche Model. 3.4.1 Field Equations. 3.4.2 Curvilinear Coordinate System in a Vertical Plane 3.4.3 The Model Equations.	115 117 123 123 125 130 131 133 135

		Table of Contents	XIX
	3.6	Avalanches with Erosion and Deposition	. 152
		3.6.1 Coordinate System	. 153
		3.6.2 Accumulation and Deposition	. 154
		3.6.3 The Model Equations	. 156
	3.7	Granular Flows in Rotating Drums	
		3.7.1 Solid-Like and Fluid-Like Regions	. 158
		3.7.2 Coordinate System	
		3.7.3 Governing Equations in a Solid Rotating Body	
		3.7.4 Interfacial Conditions and Scalings	
		3.7.5 Governing Equations in the Avalanche Region	
	3.8	Summary	. 165
4	Ava	lanches in Arbitrarily Curved and Twisted Channels .	. 167
	4.1	Motivation	
	4.2	The Essence of the New Theory	
	4.3	General Orthogonal Coordinate System	
	4.4	Non-Dimensional Equations	
		4.4.1 Components of the Gravitational Acceleration	
		4.4.2 Balance Equations	
		4.4.3 Kinematic Surface Conditions	
		4.4.4 Traction-Free Condition at the Free Surface	
		4.4.5 The Coulomb Sliding Law at the Base	
	4.5	Depth Integration	
	4.6	Ordering	
	4.7	Closure	
	4.8	Flow Profile	
	4.9	The Model Equations in Conservative Form	. 198
		4.9.1 Avalanche Motions Down Curved	
		and Twisted Channels	
		4.9.2 The Importance of the New Theory	
		4.9.3 The Standard Form of the Differential Equations	
		4.9.4 Characteristic Speeds and Critical Flow	
	4.10	Erosion and Deposition for the Full Set of Equations	
		4.10.1 Inclusion of Erosion and Deposition	
		4.10.2 Functional Relation for Erosion and Deposition	
	4.11	Discussion	
		4.11.1 Summary and Embedding of Earlier Models	. 207
		4.11.2 The Orthogonal Complex	
		vs. the Orthogonal General System	
	4.12	Concluding Remarks and Future Outlook	. 210

5	Exa	act and Semi-Exact Solutions of the Model Equations 213
	5.1	Solutions of the Model Equations
		5.1.1 A Complete Analytical Solution
		5.1.2 Particular Solutions
		5.1.3 Numerical Solutions
	5.2	One-Dimensional Similarity Solutions
		5.2.1 One-Dimensional Flow Down Inclined Planes 215
		5.2.2 Flow Over an Arbitrarily Curved and Twisted Channel 224
		5.2.3 Moderately Curved Beds
		5.2.4 Variable Bed Friction
		5.2.5 Variable Bed Friction,
		Curved Bed and Voellmy Drag 249
	5.3	Two-Dimensional Similarity Solutions
6	Exa	act Solutions for Flow Avalanches in Rotating Drums 265
	6.1	A Simple Exact Solution for Steady Flow in a Rotating
		Drum Without Erosion and Deposition
		6.1.1 Coordinate System, Geometry
		of the Drum and the Moving Mass
		6.1.2 Avalanche Depth Determined Without Wall Friction 267
		6.1.3 Avalanche Depth Determined by Including
	<i>c</i> o	Wall Friction
	6.2	An Exact Solution for Steady Flow in a Slowly Rotating
		Drum with Erosion and Deposition
		6.2.1 A Steady Flow Avalanche
	c o	6.2.2 An Exact Solution
	6.3	Mixing in a Rotating Drum
		6.3.1 Particle Paths
	6.4	6.3.2 Circuit Time
	0.4	and Mixing of Granular Material in a Rotating Cylinder 282
		6.4.1 Model
		6.4.2 Experiments
		6.4.3 Results and Discussion
	6.5	Concluding Remarks
	0.0	200
Par	rt III	I Shock Capturing Numerical Methods
		nulations of Free Surface Flows of Shallow
Ava	alanc	hes Sliding Over Curved and Twisted Channels
7	Cla	ssical and High Resolution Shock-Capturing
		merical Methods
	7.1	Classical Eulerian and Lagrangean Approaches 298
		7.1.1 Eulerian Approach
		7.1.2 LAGRANGEAN Approach

		Table of Contents	XXI
	7.2	Some Traditional Numerical Methods	
		7.2.1 First-Order Schemes	
		7.2.2 Second-Order Schemes	
	7.3	Appropriate Numerical Modelling	
	7.4	Modern Numerical Methods	
		7.4.1 Total Variation Diminishing Method	
		7.4.2 Second-Order TVD Schemes	
		7.4.3 Cell Reconstruction with Slope Limiters	
		7.4.4 Non-Linear Conservation Law and TVD Methods	
		7.4.5 TVD LAX-FRIEDRICHS Method	
		7.4.6 Modified TVDLF Scheme	
	7.5	NOC Schemes	
	7.6	Alternative Numerical Schemes	
	7.7	Summary	328
8	Two	o-Dimensional Shock-Capturing Schemes	
		Avalanching Flow	329
	8.1	The Two-Dimensional LAGRANGEan Techniques	
	8.2	The Two-Dimensional NOC Schemes	
		8.2.1 Description	331
		8.2.2 Predictor Step	
		8.2.3 Corrector Step	337
	8.3	Two-Dimensional Shock-Capturing Methods Applied	
		to the Extended Avalanche Equations	338
	8.4	Summary	341
9	Ava	lanche Simulations over Curved and Twisted Channels	343
	9.1	Performance of Various Numerical Schemes	343
		9.1.1 Numerical Performances	344
	9.2	Effects of Topographic Variations	350
		9.2.1 Constant Cross-Slope Curvature	
		9.2.2 Variable Cross-Slope Curvature	356
	9.3	Superimposed Basal Topography	
	9.4	Avalanches Sliding Down Curved and Twisted Channels	363
		9.4.1 Flows Through Uniformly Curved	
		and Twisted Channels	364
		9.4.2 Avalanching Flows Through Non-Uniformly Curved	
		and Twisted Channels	
	9.5	Sensitivity to Phenomenological Parameters	
	9.6	Pressure Dependence of the Friction Angles	
		9.6.1 Mass-Dependent Bed Friction Angle	378
		9.6.2 Scale Effects Due to the Pressure Dependence of $\delta \dots$	379
	9.7	Formation of Shocks	381
	9.8	Summary	385

## Part IV Experimental Validation of the Theoretical Prediction with Different Measurement Techniques

10	Experimental Findings and a Comparison
	with the Theory
	10.1 Why Are Laboratory Experiments Performed?
	What Can be Inferred from Them?
	10.2 Chute Flow Experiments
	10.2.1 Experimental Set-Up
	10.2.2 Experimental Procedure
	10.2.3 Measurement of Phenomenological Coefficients 399
	10.2.4 Results
	10.2.5 Variable Bed Friction Angle (Position-Dependent) 409
	10.2.6 Chutes with a Convex Curved Bump
	10.2.7 Limitation of the Model
	10.3 Avalanche Flow Without Side Confinement 417
	10.3.1 Experimental Set-Up
	10.3.2 Rolled Surfaces
	10.4 Channelised Avalanche Flows
	10.5 Avalanches Across Irregular Three-Dimensional Terrain 436
	10.5.1 The Table-Top Experiments
	10.5.2 Further Verification of the Model Equations 446
11	Particle Image Velocimetry for Free Surface Flow
	Avalanches
	11.1 Introduction
	11.2 Particle Image Velocimetry Technique
	11.2.1 Image Intensity Field
	11.2.2 Cross-Correlation Function
	11.2.3 Spatial Resolution
	11.2.4 Summary of the PIV System
	11.3 Experimental Set-Up for Granular Avalanches
	11.3.1 Transparent Fluids and the Usual PIV Set-Up 467
	11.3.2 Set-Up for Granular Avalanches
	11.3.3 Technical Details
	11.4 Experimental Peculiarities Arising for Granular Materials 468
	11.4.1 General Errors
	11.4.2 Particular Errors for Granular Flows 469
	11.5 Post-Processing and Evaluation
	11.6 PIV with Multi-Cameras
	11.7 Particle Tracking Velocimetry (PTV) Measuring Technique 475

12		lanche Experiments Using the PIV Measurement				
	Technique 4					
	12.1	Experimental Details	480			
		Measurement of Avalanche Depth Profiles				
	12.3	Validation of the Theory	484			
		12.3.1 Experiments Using Small-Cap and Quartz Particles	484			
		12.3.2 The PIV Measurement and Validation of the Theory	486			
		12.3.3 Evolution of the Avalanche Geometry	490			
		12.3.4 Multi-CCD Cameras and Velocity Shearing	490			
	12.4	Is There a Terminal Velocity on Inclined Planes?				
		12.4.1 Background	493			
		12.4.2 Remarks on Experimental Procedures	495			
		12.4.3 Results	495			
		12.4.4 Summary	502			
	12.5	Concluding Remarks	503			
Par	rt V	Avalanche Protection and Defence Structures				
13	Pro	tection Against Snow Avalanche Hazards	507			
		Types of Avalanche Protection				
		13.1.1 Avalanche Initiation and Protective Measures	508			
		13.1.2 Early Efforts				
		13.1.3 Modern Methods of Avalanche Defence and Protection	510			
	13.2	Avalanche Protection in Different Countries	514			
		13.2.1 Avalanche Protection in Switzerland	514			
		13.2.2 Avalanche Protection in France	515			
		13.2.3 Avalanche Protection in Iceland	516			
		13.2.4 Snow Avalanche Protection in Austria	518			
		13.2.5 Snow Avalanche Barriers in North America				
	13.3	Laboratory Experiments: A Means to Design Defence				
		Structures	519			
		13.3.1 Laboratory Models and Experiments	520			
		13.3.2 Simulation of Avalanche Protection				
		13.3.3 A Structural Protection Technique by Deflection	525			
	13.4	Conclusion				
14	Sun	nmary and Outlook	520			
14		Knowledge at Present				
	1-1.1	14.1.1 Theory				
		14.1.2 Numerics				
		14.1.3 Experiments				
	149	Attempts in Future				
	14.4	14.2.1 Application in Nature				
		14.2.2 Application in the Laboratory				
		14.2.2 Application in the Dabotatory	999			

## XXIV Table of Contents

14.2.3	Advancing the Numerics	536
14.2.4	More Advanced Measurement Techniques and Experiments	526
References		539
Name Index .		565
$\mathbf{Index}\dots\dots$		571