

Contents

Foreword	xvii
Preface	xix
About the Editors	xxiii
Contributors	xxv

I

GENERAL INTRODUCTION

1. Challenges of High Dam Construction to Computational Mechanics

CHUHAN ZHANG

1.1 Background	4
1.1.1 Hydropower Development	4
1.1.2 Transbasin Water Transfer	4
1.1.3 Building High Dams for Power Development and Water Transfer	7
1.2 Building more Bridges between Computational Mechanics and Large Dam Engineering	9
1.2.1 Introduction	9
1.2.2 Key Issues for Safety Evaluation of Large Dams and Power Plants	10
1.3 Research Examples Completed by the National Laboratory of High Dams and Large Structures at Tsinghua	20
1.3.1 Seismic Response of Arch Dams Considering Canyon Radiation Damping and Joint Opening	21
1.3.2 Nonlinear Fracture Analysis of Arch Dams	24
1.3.3 Failure Analysis of Arch Dam Foundations	32
1.4 Conclusions	38
References	39

2. The Performance of Dams During the Wenchuan 5–12 Earthquake and Lessons Learned from the Event

CHUHAN ZHANG

2.1 Introduction	46
2.2 Performance of Hydroprojects and High Dams	47
2.3 Lessons Learned on Hydraulic Structures in Relation to the Wenchuan 5–12 Event	52

2.3.1 Lesson 1: General Comments on the Performance of Dams and Hydropower Structures, and Safety Criteria to Resist Earthquakes	53
2.3.2 Lesson 2: Earthquake and Reservoir Impounding	55
2.3.3 Lesson 3: Secondary Disasters under a Series of Earthquake and Geological Catastrophes	58
2.3.4 Lesson 4: Rescue Measures During Earthquakes and Operational Maintenance of High Dam Auxiliary Facilities	63
2.4 Conclusions	64
Acknowledgments	64
References	65

3. Seismic Safety Evaluation of High Concrete Dams

CHUHAN ZHANG, FENG JIN

3.1 Introduction	68
3.2 Conventional Seismic Design Practice	69
3.3 Advanced Seismic Design and Research	70
3.3.1 Effects of Earthquake Input Mechanism and Radiation Damping Due to Infinite Canyon	70
3.3.2 Effects of Nonlinearity of Contraction Joint Opening	71
3.3.3 Effects of Damage and Fracture Behavior in Dams and Strengthening	72
3.3.4 Effects of Dam—Reservoir Interaction	74
3.3.5 Earthquake Stability of Dam—Abutment System	74
3.4 Conclusions	75
References	75

4. Seismic Safety Evaluation of High Concrete Dams

CHUHAN ZHANG, FENG JIN, JIANWEN PAN, YUCHUAN LONG

4.1 Introduction	80
4.1.1 General Description	80
4.1.2 Material Parameters, Loading Conditions and Design Earthquake	80
4.2 Computational Results	81
4.2.1 Comparison Study on Canyon Response by Different Foundation Input Models	81
4.2.2 Comparison Study on Linear Elastic Response of the Dam by Different Foundation Input Models	84
4.2.3 Comparison Study on Contraction Joint Opening of the Dam by Different Foundation Input Models	86
4.2.4 Comparison Study on Damage-Cracking of the Dam by Different Foundation Input Models	88
4.2.5 Strengthening of the Dam to Resist the Design Earthquakes	93
4.3 Conclusions	97
Acknowledgments	98
References	98

5. A Primary Digital Dam Simulation System for an Arch Dam

FENG JIN, JIAN YANG, JINTING WANG

5.1 Introduction	102
------------------	-----

5.2 Digital Dam Simulation System	102
5.2.1 Description of the Digital Dam Simulation System	102
5.2.2 Pilot Primary Model of Digital Dam Simulation System	103
5.3 Simulation Model of an Arch Dam	104
5.3.1 Finite Element Model	104
5.3.2 Material Parameters	106
5.4 Inverse Analysis	106
5.5 Structural Analysis	107
5.5.1 Regularity of Dam Displacements	107
5.5.2 Stress Analysis	110
5.6 Conclusions	113
Acknowledgments	113
References	113

II

DYNAMIC SOIL—STRUCTURE AND FLUID—STRUCTURE INTERACTIONS

6. A Coupling Procedure of Finite Element and Scaled Boundary Finite Element Methods for Soil—Structure Interaction in the Time Domain

JUNYI YAN, CHUIHAN ZHANG, FENG JIN

6.1 Introduction	118
6.2 Motion Equations of Coupling System	120
6.3 Realization and Model Approximation	121
6.3.1 Diagonalization	121
6.3.2 Decomposition	122
6.3.3 Truncation	123
6.3.4 Realization and Model Reduction	125
6.4 Evaluation of Interaction Forces	127
6.5 Numerical Verification	127
6.5.1 Accuracy	127
6.5.2 Efficiency	133
6.6 Conclusions	137
Acknowledgments	137
References	138

7. Time-Domain Analysis of Gravity Dam—Reservoir Interaction Using High-Order Doubly Asymptotic Open Boundary

XIANG WANG, FENG JIN, SURIYON PREMPRAMOTE, CHONGMIN SONG

7.1 Introduction	140
7.2 Finite Element Model of Dam—Reservoir System	143
7.3 Scaled Boundary Finite Element Method for Semi-infinite Reservoir with Constant Depth	145
7.4 Modal Decomposition of Scaled Boundary Finite Element Equation	149
7.5 Doubly Asymptotic Continued Fraction Solution for Modal Dynamic Stiffness	151

7.6 High-Order Doubly Asymptotic Open Boundary	155
7.7 Numerical Implementation in Time Domain	157
7.8 Numerical Examples	160
7.8.1 Rigid Dam	161
7.8.2 Flexible Dam	165
7.9 Conclusions	169
References	169

8. Finite Element Analysis of Dam—Reservoir Interaction Using High-Order Doubly Asymptotic Open Boundary

YICHAO GAO, FENG JIN, XIANG WANG, JINTING WANG

8.1 Introduction	174
8.2 Modeling of Dam—Reservoir System	177
8.3 Summary of the Scaled Boundary Finite Element Method for Semi-infinite Reservoir with Constant Depth	179
8.4 High-Order Doubly Asymptotic Open Boundary for Hydrodynamic Pressure	182
8.4.1 Modal Decomposition of Scaled Boundary Finite Element Equation	182
8.4.2 Doubly Asymptotic Continued Fraction Solution for Modal Dynamic Stiffness	183
8.4.3 High-Order Doubly Asymptotic Open Boundary	184
8.5 Coupled Numerical Methods for Dam—Reservoir Interaction Analysis	185
8.5.1 Direct Coupled Method	185
8.5.2 Partitioned Coupled Method	188
8.6 Numerical Examples	191
8.6.1 Gravity Dam	191
8.6.2 Arch Dam	194
8.7 Conclusions	196
Acknowledgments	197
References	197

9. Analytical Solutions for Dynamic Pressures of Coupling Fluid—Porous Medium—Solid due to SV-Wave Incidence

JINTING WANG, CHUHAN ZHANG, FENG JIN

9.1 Introduction	200
9.2 Governing Equations	201
9.2.1 Linear Elastic Rock Foundation	201
9.2.2 Porous Medium (Fully or Partially Saturated)	202
9.2.3 Ideal Compressible Fluid	203
9.3 Boundary Conditions	203
9.3.1 Interface between Elastic Solid and Porous Medium ($y=0$)	204
9.3.2 Interface between Porous Medium and Ideal Fluid ($y=h$)	204
9.3.3 Free Surface of Ideal Fluid ($y=H$)	205
9.3.4 Interface between Elastic Solid and Ideal Fluid ($y=0$ and $h=0$)	205
9.4 Formulations of the System	206

9.5 Numerical Example	207
9.6 Discussion of Factors Influencing Dynamic Pressures	208
9.6.1 Influence of Degree of Saturation of the Porous Medium	208
9.6.2 Influences of Thickness of the Porous Medium	210
9.6.3 Influence of Incidence Angle	215
9.6.4 Influence of Permeability of the Porous Medium	216
9.7 Conclusions	216
Appendix	217
Acknowledgments	220
References	220

10. Modification of Equation of Motion of Fluid-Conveying Pipe for Laminar and Turbulent Flow Profiles

CHANGQING GUO, CHUHAN ZHANG, M.P. PAÏDOUSSIS

10.1 Introduction	222
10.2 Modification of the Centrifugal Force Term of the Equation of Motion of the Fluid-Conveying Pipe	222
10.3 Flow-Profile-Modification Factors with Different Flow Profiles	224
10.3.1 Laminar Flow in Circular Pipe	224
10.3.2 Turbulent Flow in Circular Pipe	225
10.4 Equivalent Flow Velocity and Equivalent Mass	231
10.5 Critical Flow Velocities for Pipes Conveying Fluid for Different Flow Profiles	232
10.5.1 Critical Flow Velocities for Divergence	232
10.5.2 Critical Flow Velocities for Flutter	233
10.6 Conclusions	235
Acknowledgments	236
References	236

III

NONLINEAR EARTHQUAKE RESPONSE OF CONCRETE DAMS

11. Influence of Seismic Input Mechanisms and Radiation Damping on Arch Dam Response

CHUHAN ZHANG, JIANWEN PAN, JINTING WANG

11.1 Introduction	242
11.2 Earthquake Input Mechanisms and Verification	244
11.2.1 Massless Foundation Input Model	244
11.2.2 Mass Foundation and Viscous-Spring Boundary Input Model	244
11.3 Modeling of Contraction Joints	247
11.4 Comparison Study on Canyon and Dam Response by Different Input Models	250
11.4.1 Material Parameters and Design Earthquake	250
11.4.2 Finite Element Discretization	251

11.4.3	Comparison of Earthquake Responses of the Three-Dimensional Canyon	251
11.4.4	Comparison of Linear Elastic Responses of the Dam	254
11.4.5	Comparison of Nonlinear Responses of the Dam	257
11.5	Conclusions	260
	Acknowledgments	260
	References	261

12. Seismic Damage-Cracking Analysis of Arch Dams Using Different Earthquake Input Mechanisms

JIANWEN PAN, CHUHAN ZHANG, JINTING WANG, YANJIE XU

12.1	Introduction	264
12.2	Modeling of the System	265
12.2.1	Earthquake Input Mechanisms	265
12.2.2	Modeling of Contraction Joint Opening	271
12.2.3	Plastic-Damage Model for Concrete	272
12.3	Seismic Damage-Cracking Analysis of Dagangshan Arch Dam	274
12.3.1	Material Parameters and Loading Conditions	275
12.3.2	Finite Element Discretization	276
12.3.3	Results of Damage-Cracking Analysis	276
12.4	Conclusions	280
	Acknowledgments	280
	References	280

13. A Comparative Study of the Different Procedures for Seismic Cracking Analysis of Concrete Dams

JIANWEN PAN, CHUHAN ZHANG, YANJIE XU, FENG JIN

13.1	Introduction	284
13.2	Fracture Procedures	285
13.2.1	Extended Finite Element Method with Cohesive Constitutive Relation	285
13.2.2	Crack Band Finite Element Method with Plastic-Damage Model	290
13.2.3	Drucker—Prager Elastoplastic Model	292
13.2.4	Relationship of the Three Fracture Procedures	293
13.3	Benchmark Example for Accuracy Verification	294
13.4	Earthquake Fracture Analysis of Koyna Dam	297
13.5	Earthquake Cracking Analysis of an Arch Dam	301
13.6	Conclusions	307
	Acknowledgments	309
	References	309

14. Nonlinear Earthquake Analysis of High Arch Dam—Water—Foundation Rock Systems

JINTING WANG, CHUHAN ZHANG, FENG JIN

14.1	Introduction	312
14.2	Computational Model	314

14.2.1	Impounded Water	315
14.2.2	Earthquake Input Method	316
14.3	Ertan Arch Dam	317
14.3.1	Finite Element Model and Material Parameters	318
14.3.2	Ground Motion	320
14.4	Efficiency Evaluation of the Earthquake Input Method	320
14.5	Evaluation of the Proposed Model Using EACD-3D-2008	323
14.5.1	EACD-3D-2008 Model	323
14.5.2	Comparison of the Results from the Two Models	324
14.6	Earthquake Analysis of Arch Dam—Water—Foundation Rock	329
14.6.1	Cases Analyzed and Response Results	329
14.6.2	Natural Frequency of the System	331
14.6.3	Effects of Earthquake Input Mechanism	332
14.6.4	Effects of Water Compressibility	333
14.6.5	Effects of Contraction Joints	335
14.7	Conclusions	337
	Acknowledgments	338
	References	338

15. Numerical Simulation of Reinforcement Strengthening for High-Arch Dams to Resist Strong Earthquakes

YUCHUAN LONG, CHUHAN ZHANG, FENG JIN

15.1	Introduction	342
15.2	Material Constitutive Models	343
15.2.1	Plastic-Damage Model for Concrete	345
15.2.2	Constitutive Relations for Reinforced Steel	346
15.2.3	Equivalence between Increasing Steel Stiffness and Modifying Postcracking Stiffness of Concrete	349
15.3	Finite Element Formulation	350
15.3.1	Zoning Concept for Lightly Reinforced Concrete Members	350
15.3.2	Finite Element Formulation of Modified Embedded-Steel Model	351
15.3.3	Comparison between Stiffening Reinforced Steel and Modifying Postcracking Stiffness of Concrete	354
15.4	Numerical Verification	355
15.4.1	The Reinforced Concrete Slab Tested by McNeice	355
15.4.2	The Reinforced Concrete Slab Tested by Jain and Kennedy	357
15.5	Damage Analysis of the Dagangshan Arch Dam	359
15.5.1	Finite Element Mesh and Constitutive Models of Materials	359
15.5.2	Numerical Results of the Damage Analyses of the Dagangshan Arch Dam	362
15.6	Conclusions	366
	Acknowledgments	367
	References	367

16. Nonlinear Seismic Analyses of a High Gravity Dam with and without the Presence of Reinforcement

YUCHUAN LONG, CHUHAN ZHANG, YANJIE XU

16.1	Introduction	370
------	--------------	-----

16.2 Constitutive Relations of Material Components	372
16.2.1 Plastic-Damage Model for Plain Concrete	372
16.2.2 Reinforced Steel Model without Bond—Slip	374
16.2.3 Reinforced Steel Model with Bond—Slip	375
16.3 Seismic Analyses of a Gravity Dam	376
16.3.1 Finite Element Mesh and Constitutive Models of Materials	376
16.3.2 Dynamic Properties of the Jin'anqiao Gravity Dam	378
16.3.3 Seismic Damage Analyses of the Jin'anqiao Gravity Dam	380
16.4 Conclusions	384
Acknowledgments	385
References	385

17. Seismic Safety of Arch Dams with Aging Effects

JINTING WANG, FENG JIN, CHUHAN ZHANG

17.1 Introduction	388
17.2 Modeling of Chemomechanical Damage of Aging Dams	389
17.3 Nonlinear Finite Element Procedure for Seismic Analysis of Arch Dams	390
17.3.1 Modeling of Nonlinear Contraction Joint	391
17.3.2 Modeling of Foundation Rock	391
17.4 Seismic Response Analysis of Arch Dams with Aging Effects	392
17.4.1 Analysis Model	393
17.4.2 Effect of Joint Opening on Dynamic Response	397
17.4.3 Analysis of Aging Effect	400
17.5 Conclusions	402
Acknowledgments	405
References	405

IV

TOPICS RELATED TO THE SAFETY EVALUATION OF CONCRETE DAMS

18. Three-Dimensional Mode Discrete Element Method: Elastic Model

FENG JIN, CHONG ZHANG, WEI HU, JINTING WANG

18.1 Introduction	410
18.2 3MDEM	411
18.2.1 Block Description	411
18.2.2 Kinematics Equations	413
18.2.3 Deformation Mode Selection	418
18.2.4 Force Calculation	418
18.2.5 Calculation Process	421
18.3 Examples for the Linear Elastic Constitutive Model	421
18.3.1 Cantilever Beam	421
18.3.2 Impact Simulation of Pillar	423
18.3.3 Wave Propagation	426

18.4 Conclusions	427
Acknowledgments	427
References	427

19. Comparative Study Procedure for the Safety Evaluation of High Arch Dams

FENG JIN, WEI HU, JIANWEN PAN, JIAN YANG, JINTING WANG, CHUIHAN ZHANG

19.1 Introduction	430
19.2 Safety Evaluation Method	431
19.2.1 Evaluation Basis	432
19.2.2 Safety Evaluation Factors	433
19.3 Material Models and Parameters	434
19.4 Engineering Verification for the Safety Evaluation Method	436
19.4.1 Kölnbrein Arch Dam	436
19.4.2 Xiaowan Arch Dam	441
19.5 Evaluation Criteria	450
19.5.1 Introduction for Comparative Projects	451
19.5.2 Comparative Study	452
19.6 Conclusions	457
Acknowledgments	457
References	458

20. Investigation of Damping in Arch Dam—Water—Foundation Rock System of Mauvoisin Arch Dam

JINTING WANG

20.1 Introduction	460
20.2 Analysis Procedure	462
20.2.1 Idealization of Dam—Water—Foundation Rock System	462
20.2.2 Frequency Domain Equations	462
20.2.3 Response to Arbitrary Ground Motion	464
20.3 Effective Damping Ratio of Dam—Water—Foundation Rock System	465
20.3.1 Material Parameters, Ground Motion and Response Quantities	465
20.3.2 Effective Damping Ratio of Dam—Foundation Rock with Empty Reservoir	466
20.3.3 Effective Damping Ratio of Dam—Water—Foundation Rock	472
20.4 Seismic Responses of Mauvoisin Arch Dam for Two Foundation Models	477
20.4.1 Material Parameters and Ground Motion	478
20.4.2 Empty Reservoir ($H = 0$)	478
20.4.3 Partially Full Reservoir ($H = 0.9 H_s$)	482
20.5 Conclusions	484
Acknowledgments	485
References	486

21. Practical Procedure for Predicting Non-Uniform Temperature on the Exposed Face of Arch Dams

FENG JIN, ZHENG CHEN, JINTING WANG, JIAN YANG

21.1	Introduction	488
21.1.1	Nomenclature	490
21.2	Heat Conduction Equation and Boundary Conditions for Arch Dams	491
21.2.1	Heat Conduction Equation	491
21.2.2	Boundary Conditions	491
21.2.3	Heat Conduction Finite Element Modeling	492
21.3	Solar Radiation Model	493
21.3.1	ASHRAE Clear Sky Model	493
21.3.2	Algorithm for Shadow of Solar Radiation	494
21.4	Case Study	496
21.4.1	Simulation Model of the Arch Dam	496
21.4.2	Material Properties of the Dam and Foundation	497
21.4.3	Solar Irradiation Distribution on the Dam Surface	500
21.4.4	Thermal Analysis of the Arch Dam	503
21.4.5	Thermal Stress	507
21.5	Conclusions	508
	Acknowledgments	509
	References	509

22. Experimental and Numerical Study of the Geometrical and Hydraulic Characteristics of a Single Rock Fracture during Shear

XIANGBIN XIONG, BO LI, YUJING JIANG, TOMOFUMI KOYAMA, CHUHAN ZHANG

22.1	Introduction	514
22.2	Introduction to Coupled Shear–Flow Test	516
22.2.1	Description of Apparatus and Sample Preparation	516
22.2.2	Test Conditions and Procedures	518
22.2.3	Coupled Shear–Flow Test Results	519
22.3	Numerical Simulations	522
22.3.1	Governing Equations and Formulation of Problem	522
22.3.2	Models of Numerical Simulation	524
22.4	Results of Numerical Simulation	526
22.4.1	Evolution of Contact Area Distribution and Transmissivity during Shear	526
22.4.2	Evolution of Mechanical Aperture and Hydraulic Aperture during Shear	529
22.4.3	Influence of Inertial Effects of Fluid on the Transmissivity and Hydraulic Aperture	531
22.4.4	Prediction of the Relation between Mechanical Aperture and Hydraulic Aperture	533
22.5	Conclusions	535
	References	536

V

MESOSCALE MECHANICAL BEHAVIOR OF CONCRETE

23. Study on the Heterogeneity of Concrete and its Failure Behavior Using the Equivalent Probabilistic Model

XINWEI TANG, YUANDE ZHOU, CHUHAN ZHANG, M. ASCE, JIANJUN SHI

- 23.1 Introduction 542
- 23.2 Concrete Equivalent Probabilistic Model Based on Weibull Distribution Law 543
 - 23.2.1 Damage Evolution and Strength Criteria 544
 - 23.2.2 Multiaxial Stress—Strain Relation 546
 - 23.3 Improved Model of Weibull Distribution Law 546
- 23.3.1 Introducing Spatial Correlation Length Factor Θ into the Weibull Distribution Law 547
 - 23.3.2 Verification Analysis 548
- 23.4 Effect of Heterogeneity on Size Effect of Concrete: Test and Numerical Study 549
 - 23.4.1 Weibull Statistical Theory for Size Effect 550
 - 23.4.2 Uniaxial Compression Tests 553
 - 23.4.3 Comparison of Test and Simulation Results 556
- 23.5 Effect of Heterogeneity on Damage and Fracture Behavior of Koyna Gravity Dam 561
 - 23.5.1 Project Data and Finite Element Discretization 562
 - 23.5.2 Influence of Mechanical Parameter Random Distribution 565
 - 23.5.3 Influence of Heterogeneity Index 566
 - 23.5.4 Influence of Fracture Energy 567
 - 23.6 Conclusions 568
 - Acknowledgments 569
 - References 569

24. A Multiphase Mesostructure Mechanics Approach to the Study of the Fracture-Damage Behavior of Concrete

XINWEI TANG, CHUHAN ZHANG, JIANJUN SHI

- 24.1 Introduction 572
- 24.2 Preprocess of Mesoscale Numerical Simulation 573
 - 24.2.1 Random Aggregates Generation 573
 - 24.2.2 Random Aggregates Disposition Approach 574
- 24.2.3 Finite Element Mesh Coordinates Generation for Aggregates 574
 - 24.3 Mesoscopic Mechanical Model 581
 - 24.3.1 Damage Evolution and Strength Criteria 581
 - 24.3.2 Multiaxial Stress—Strain Relation 582
- 24.4 Statistical Distribution of Heterogeneity for Concrete Parameters 583
 - 24.4.1 Theory of the Weibull Distribution 583
 - 24.4.2 Effect of Heterogeneity of Parameters on Macroscopic Response 584

24.5	Study on Mechanical Behaviors of Rockfill Concrete	586
24.5.1	Experimental Tests for Determining Basic Mechanical Parameters of Three Components	586
24.5.2	Four-Point Flexural Beam Tests and Numerical Simulations	589
24.6	Conclusions	592
	Acknowledgments	593
	References	593

25. Numerical Study of Dynamic Behavior of Concrete by Mesoscale Particle Element Modeling

CHUAN QIN, CHUHAN ZHANG

25.1	Introduction	596
25.2	Brief Introduction to the Preprocessing of the Mesoscale Concrete Model	598
25.3	Inverse Method for Mesoparameters	599
25.3.1	Solution Scheme of Particle Flow Code	599
25.3.2	Determination of Mesoparameters by Inverse Analysis	600
25.4	Numerical Simulations of Dynamic Splitting Tensile Tests at Different Strain Rates	603
25.4.1	Load--Deformation Relationship and Dynamic Increase Factor	604
25.4.2	Failure Patterns of Specimens	606
25.4.3	Variation in Consumed Energy Components	608
25.4.4	Force Chain Distribution of Splitting Tension Tests	608
25.5	Numerical Simulations of Dynamic Uniaxial Compression Tests at Different Strain Rates	609
25.5.1	Stress--Strain Relationship and Dynamic Increase Factor	609
25.5.2	Failure Patterns of Uniaxial Compression Tests	612
25.5.3	Variation of Different Energy Components	612
25.5.4	Force Chain Distribution of Uniaxial Compression Tests	613
25.6	Conclusions	614
	Acknowledgments	616
	References	616

Index 619