

Contents

Preface xiii

Acknowledgments xv

1 Introduction 1

- 1.1 Earthquake Experience: Cases with Strongest Shaking 1
- 1.2 Complexity of the Problem 6
- 1.3 Traditional Design Procedures: Gravity Dams 8
 - 1.3.1 Traditional Analysis and Design 8
 - 1.3.2 Earthquake Performance of Koyna Dam 9
 - 1.3.3 Limitations of Traditional Procedures 9
- 1.4 Traditional Design Procedures: Arch Dams 11
 - 1.4.1 Traditional Analysis and Design 11
 - 1.4.2 Limitations of Traditional Procedures 12
- 1.5 Unrealistic Estimation of Seismic Demand and Structural Capacity 13
- 1.6 Reasons Why Standard Finite-Element Method is Inadequate 13
- 1.7 Rigorous Methods 14
- 1.8 Scope and Organization 16

PART I: GRAVITY DAMS

2 Fundamental Mode Response of Dams Including Dam–Water Interaction 21

- 2.1 System and Ground Motion 21
- 2.2 Dam Response Analysis 22
 - 2.2.1 Frequency Response Function 22
 - 2.2.2 Earthquake Response: Horizontal Ground Motion 23
- 2.3 Hydrodynamic Pressures 24
 - 2.3.1 Governing Equation and Boundary Conditions 24
 - 2.3.2 Solutions to Boundary Value Problems 26
 - 2.3.3 Hydrodynamic Forces on Rigid Dams 28
 - 2.3.4 Westergaard's Results and Added Mass Analogy 30
- 2.4 Dam Response Analysis Including Dam–Water Interaction 32
- 2.5 Dam Response 33
 - 2.5.1 System Parameters 33
 - 2.5.2 System and Cases Analyzed 34

2.5.3	Dam–Water Interaction Effects	34
2.5.4	Implications of Ignoring Water Compressibility	37
2.5.5	Comparison of Responses to Horizontal and Vertical Ground Motions	39
2.6	Equivalent SDF System: Horizontal Ground Motion	40
2.6.1	Modified Natural Frequency and Damping Ratio	40
2.6.2	Evaluation of Equivalent SDF System	42
2.6.3	Hydrodynamic Effects on Natural Frequency and Damping Ratio	43
2.6.4	Peak Response	45
	Appendix 2: Wave-Absorptive Reservoir Bottom	46
3	Fundamental Mode Response of Dams Including Dam–Water–Foundation Interaction	49
3.1	System and Ground Motion	50
3.2	Dam Response Analysis Including Dam–Foundation Interaction	51
3.2.1	Governing Equations: Dam Substructure	51
3.2.2	Governing Equations: Foundation Substructure	52
3.2.3	Governing Equations: Dam–Foundation System	53
3.2.4	Dam Response Analysis	54
3.3	Dam–Foundation Interaction	54
3.3.1	Interaction Effects	54
3.3.2	Implications of Ignoring Foundation Mass	55
3.4	Equivalent SDF System: Dam–Foundation System	56
3.4.1	Modified Natural Frequency and Damping Ratio	56
3.4.2	Evaluation of Equivalent SDF System	57
3.4.3	Peak Response	59
3.5	Equivalent SDF System: Dam–Water–Foundation System	60
3.5.1	Modified Natural Frequency and Damping Ratio	60
3.5.2	Evaluation of Equivalent SDF System	61
3.5.3	Peak Response	62
	Appendix 3: Equivalent SDF System	63
4	Response Spectrum Analysis of Dams Including Dam–Water–Foundation Interaction	65
4.1	Equivalent Static Lateral Forces: Fundamental Mode	66
4.1.1	One-Dimensional Representation	66
4.1.2	Approximation of Hydrodynamic Pressure	67
4.2	Equivalent Static Lateral Forces: Higher Modes	68
4.3	Response Analysis	70
4.3.1	Dynamic Response	70
4.3.2	Total Response	70
4.4	Standard Properties for Fundamental Mode Response	71
4.4.1	Vibration Period and Mode Shape	71
4.4.2	Modification of Period and Damping: Dam–Water Interaction	72
4.4.3	Modification of Period and Damping: Dam–Foundation Interaction	72

4.4.4	Hydrodynamic Pressure	73
4.4.5	Generalized Mass and Earthquake Force Coefficient	74
4.5	Computational Steps	74
4.6	CADAM Computer Program	76
4.7	Accuracy of Response Spectrum Analysis Procedure	77
4.7.1	System Considered	77
4.7.2	Ground Motions	77
4.7.3	Response Spectrum Analysis	78
4.7.4	Comparison with Response History Analysis	79
5	Response History Analysis of Dams Including Dam–Water–Foundation Interaction	83
5.1	Dam–Water–Foundation System	83
5.1.1	Two-Dimensional Idealization	83
5.1.2	System Considered	84
5.1.3	Ground Motion	85
5.2	Frequency-Domain Equations: Dam Substructure	86
5.3	Frequency-Domain Equations: Foundation Substructure	87
5.4	Dam–Foundation System	88
5.4.1	Frequency-Domain Equations	88
5.4.2	Reduction of Degrees of Freedom	89
5.5	Frequency–Domain Equations: Fluid Domain Substructure	90
5.5.1	Boundary Value Problems	90
5.5.2	Solutions for Hydrodynamic Pressure Terms	91
5.5.3	Hydrodynamic Force Vectors	92
5.6	Frequency-Domain Equations: Dam–Water–Foundation System	93
5.7	Response History Analysis	94
5.8	EAGD-84 Computer Program	95
	Appendix 5: Water–Foundation Interaction	96
6	Dam–Water–Foundation Interaction Effects in Earthquake Response	101
6.1	System, Ground Motion, Cases Analyzed, and Spectral Ordinates	101
6.1.1	Pine Flat Dam	101
6.1.2	Ground Motion	103
6.1.3	Cases Analyzed and Response Results	103
6.2	Dam–Water Interaction	105
6.2.1	Hydrodynamic Effects	105
6.2.2	Reservoir Bottom Absorption Effects	107
6.2.3	Implications of Ignoring Water Compressibility	108
6.3	Dam–Foundation Interaction	112
6.3.1	Dam–Foundation Interaction Effects	112
6.3.2	Implications of Ignoring Foundation Mass	112
6.4	Dam–Water–Foundation Interaction Effects	115

7	Comparison of Computed and Recorded Earthquake Responses of Dams	117
7.1	Comparison of Computed and Recorded Motions	117
7.1.1	Choice of Example	117
7.1.2	Tsuruda Dam and Earthquake Records	118
7.1.3	System Analyzed	119
7.1.4	Comparison of Computed and Recorded Responses	120
7.2	Koyna Dam Case History	122
7.2.1	Koyna Dam and Earthquake Damage	122
7.2.2	Computed Response of Koyna Dam	123
7.2.3	Response of Typical Gravity Dam Sections	126
7.2.4	Response of Dams with Modified Profiles	127
	Appendix 7: System Properties	129

PART II: ARCH DAMS

8	Response History Analysis of Arch Dams Including Dam–Water–Foundation Interaction	133
8.1	System and Ground Motion	133
8.2	Frequency-Domain Equations: Dam Substructure	136
8.3	Frequency-Domain Equations: Foundation Substructure	137
8.4	Dam–Foundation System	138
8.4.1	Frequency-Domain Equations	138
8.4.2	Reduction of Degrees of Freedom	139
8.5	Frequency-Domain Equations: Fluid Domain Substructure	140
8.6	Frequency-Domain Equations: Dam–Water–Foundation System	142
8.7	Response History Analysis	143
8.8	Extension to Spatially Varying Ground Motion	144
8.9	EACD-3D-2008 Computer Program	146
9	Earthquake Analysis of Arch Dams: Factors to Be Included	149
9.1	Dam–Water–Foundation Interaction Effects	149
9.1.1	Dam–Water Interaction	150
9.1.2	Dam–Foundation Interaction	151
9.1.3	Dam–Water–Foundation Interaction	153
9.1.4	Earthquake Responses	153
9.2	Bureau of Reclamation Analyses	153
9.2.1	Implications of Ignoring Foundation Mass	156
9.2.2	Implications of Ignoring Water Compressibility	157
9.3	Influence of Spatial Variations in Ground Motions	158
9.3.1	January 13, 2001 Earthquake	159
9.3.2	January 17, 1994 Northridge Earthquake	160
10	Comparison of Computed and Recorded Motions	163
10.1	Earthquake Response of Mauvoisin Dam	163
10.1.1	Mauvoisin Dam and Earthquake Records	163
10.1.2	System Analyzed	165
10.1.3	Spatially Varying Ground Motion	166
10.1.4	Comparison of Computed and Recorded Responses	166

10.2	Earthquake Response of Pacoima Dam	168
10.2.1	Pacoima Dam and Earthquake Records	168
10.2.2	System Analyzed	171
10.2.3	Comparison of Computed and Recorded Responses: January 13, 2001 Earthquake	172
10.2.4	Comparison of Computed Responses and Observed Damage: Northridge Earthquake	172
10.3	Calibration of Numerical Model: Damping	174
11	Nonlinear Response History Analysis of Dams	177
	Part A: Nonlinear Mechanisms and Modeling	178
11.1	Limitations of Linear Dynamic Analyses	178
11.2	Nonlinear Mechanisms	178
11.2.1	Concrete Dams	178
11.2.2	Foundation Rock	181
11.2.3	Impounded Water	181
11.2.4	Pre-Earthquake Static Analysis	181
11.3	Nonlinear Material Models	182
11.3.1	Concrete Cracking	182
11.3.2	Contraction Joints: Opening, Closing, and Sliding	183
11.3.3	Lift Joints and Concrete–Rock Interfaces: Sliding and Separation	184
11.3.4	Discontinuities in Foundation Rock	185
11.4	Material Models in Commercial Finite-Element Codes	185
	Part B: Direct Finite-Element Method	186
11.5	Concepts and Requirements	186
11.6	System and Ground Motion	187
11.6.1	Semi-Unbounded Dam–Water–Foundation System	187
11.6.2	Earthquake Excitation	189
11.7	Equations of Motion	191
11.8	Effective Earthquake Forces	193
11.8.1	Forces at Bottom Boundary of Foundation Domain	193
11.8.2	Forces at Side Boundaries of Foundation Domain	194
11.8.3	Forces at Upstream Boundary of Fluid Domain	195
11.9	Numerical Validation of the Direct Finite Element Method	196
11.9.1	System Considered and Validation Methodology	196
11.9.2	Frequency Response Functions	199
11.9.3	Earthquake Response History	200
11.10	Simplifications of Analysis Procedure	201
11.10.1	Using 1D Analysis to Compute Effective Earthquake Forces	201
11.10.2	Ignoring Effective Earthquake Forces at Side Boundaries	203
11.10.3	Avoiding Deconvolution of the Surface Free-Field Motion	203
11.10.4	Ignoring Effective Earthquake Forces at Upstream Boundary of Fluid Domain	206
11.10.5	Ignoring Sediments at the Reservoir Boundary	207
11.11	Example Nonlinear Response History Analysis	211
11.11.1	System and Ground Motion	211
11.11.2	Computer Implementation	212
11.11.3	Earthquake Response Results	213
11.12	Challenges in Predicting Nonlinear Response of Dams	215

PART III: DESIGN AND EVALUATION

12	Design and Evaluation Methodology	219
12.1	Design Earthquakes and Ground Motions	219
12.1.1	ICOLD and FEMA	220
12.1.2	U.S. Army Corps of Engineers (USACE)	221
12.1.3	Division of Safety of Dams (DSOD), State of California	221
12.1.4	U.S. Federal Energy Regulatory Commission (FERC)	221
12.1.5	Comments and Observations	221
12.2	Progressive Seismic Demand Analyses	224
12.3	Progressive Capacity Evaluation	226
12.4	Evaluating Seismic Performance	227
12.5	Potential Failure Mode Analysis	228
13	Ground-Motion Selection and Modification	231
	Part A: Single Horizontal Component of Ground Motion	232
13.1	Target Spectrum	232
13.1.1	Uniform Hazard Spectrum	232
13.1.2	Uniform Hazard Spectrum Versus Recorded Ground Motions	232
13.1.3	Conditional Mean Spectrum	234
13.1.4	CMS-UHS Composite Spectrum	235
13.2	Ground-Motion Selection and Amplitude Scaling	239
13.3	Ground-Motion Selection to Match Target Spectrum Mean and Variance	241
13.4	Ground-Motion Selection and Spectral Matching	243
13.5	Amplitude Scaling Versus Spectral Matching of Ground Motions	247
	Part B: Two Horizontal Components of Ground Motion	247
13.6	Target Spectra	247
13.7	Selection, Scaling, and Orientation of Ground-Motion Components	250
	Part C: Three Components of Ground Motion	252
13.8	Target Spectra and Ground-Motion Selection	252
14	Application of Dynamic Analysis to Evaluate Existing Dams and Design New Dams	253
14.1	Seismic Evaluation of Folsom Dam	253
14.2	Seismic Design of Olivenhain Dam	257
14.3	Seismic Evaluation of Hoover Dam	261
14.4	Seismic Design of Dagangshan Dam	265
	References	271
	Notation	281
	Index	291