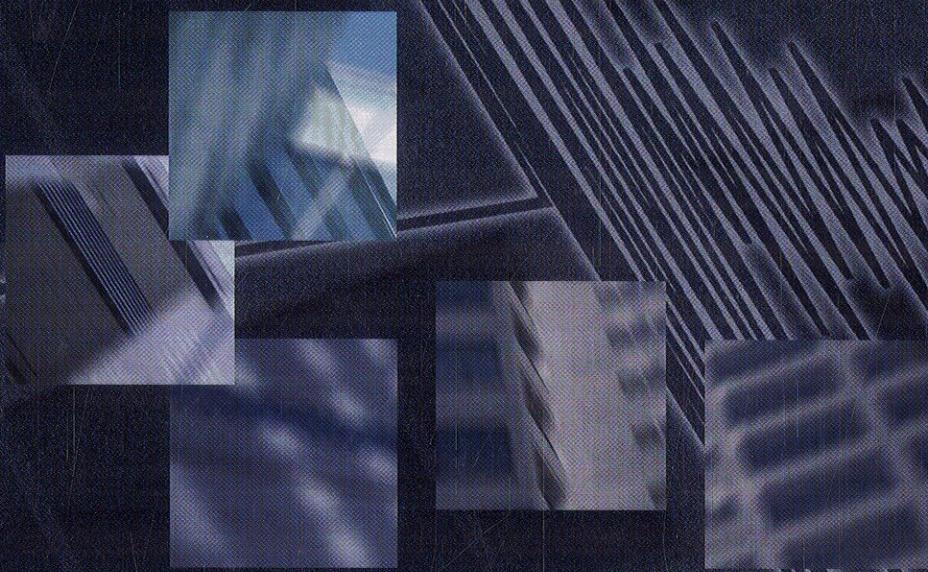


# Fundamentals of SEISMIC LOADING ON STRUCTURES

Tapan K. Sen



 WILEY

# Contents

<b>Preface</b>	<b>xv</b>
<b>Acknowledgements</b>	<b>xvii</b>
<b>1 Introduction to Earthquakes</b>	<b>1</b>
1.1 A Historical Perspective	1
1.1.1 <i>Seismic Areas of the World</i>	4
1.1.2 <i>Types of Failure</i>	5
1.1.3 <i>Fault Movement and its Destructive Action</i>	7
1.2 The Nature of Earthquakes	8
1.3 Plate Tectonics	9
1.3.1 <i>Types of Plate Boundaries</i>	10
1.3.2 <i>Convergent and Divergent Boundaries</i>	11
1.3.3 <i>Seismicity and Plate Tectonics</i>	12
1.4 Focus and Epicentre	14
1.5 Seismic Waves	14
1.5.1 <i>Body Waves</i>	15
1.5.2 <i>Surface Waves</i>	17
1.6 Seismometers	17
1.6.1 <i>Early Seismographs</i>	18
1.6.2 <i>Modern Developments</i>	20
1.6.3 <i>Locating the Epicentre</i>	22
1.7 Magnitude and Intensity	22
1.7.1 <i>Magnitude Scales</i>	23
1.7.2 <i>Seismic Moment</i>	24
1.7.3 <i>Intensity Scales</i>	25
1.8 Reid's Elastic Rebound Theory	27
1.9 Significant Milestones in Earthquake Engineering	27
1.10 Seismic Tomography	28
1.10.1 <i>The Challenges Ahead</i>	32
1.11 References	32
<b>2 Single Degree of Freedom Systems</b>	<b>35</b>
2.1 Introduction	35
2.2 Free Vibration	38

2.2.1	<i>Equations of Motion with Damping</i>	40
2.2.2	<i>Damping Ratio</i>	41
2.2.3	<i>Treatment of Initial Conditions</i>	42
2.3	Periodic Forcing Function	42
2.3.1	<i>Magnification Factors</i>	46
2.3.2	<i>Damping</i>	46
2.3.3	<i>Support Motion</i>	48
2.4	Arbitrary Forcing Function	49
2.4.1	<i>Duhamel Integral</i>	49
2.4.2	<i>Numerical Evaluation</i>	50
2.4.3	<i>Worked Example – Duhamel Integral</i>	52
2.5	References	53
<b>3</b>	<b>Systems with Many Degrees of Freedom</b>	<b>55</b>
3.1	Introduction	55
3.2	Lumped Parameter Systems with Two Degrees of Freedom	55
3.3	Lumped Parameter Systems with more than Two Degrees of Freedom	56
3.3.1	<i>Free Vibration</i>	58
3.3.2	<i>A Worked Example (Two degrees of Freedom System)</i>	60
3.3.3	<i>Normalization of Mode Shapes</i>	62
3.3.4	<i>Orthogonality of Mode Shapes</i>	63
3.3.5	<i>Worked Example – Orthogonality Check</i>	64
3.4	Mode Superposition	65
3.4.1	<i>Use of Normal or Generalized Coordinates</i>	65
3.5	Damping Orthogonality	67
3.6	Non-linear Dynamic Analysis	68
3.6.1	<i>Introduction</i>	68
3.6.2	<i>Incremental Integration Process</i>	68
3.6.3	<i>Numerical Procedures for Integration</i>	69
3.6.4	<i>Estimate of Errors</i>	71
3.6.5	<i>Houbolt's Method</i>	72
3.6.6	<i>Explicit and Implicit Scheme</i>	73
3.6.7	<i>Minimum Time Step <math>\Delta t</math> (Explicit Integration Scheme)</i>	73
3.7	References	73
<b>4</b>	<b>Basics of Random Vibrations</b>	<b>75</b>
4.1	Introduction	75
4.2	Concepts of Probability	76
4.2.1	<i>Random Variable Space</i>	76
4.2.2	<i>Gaussian or Normal Distribution</i>	81
4.2.3	<i>Worked Example with Standard Normal Variable</i>	84
4.3	Harmonic Analysis	85
4.3.1	<i>Introduction</i>	85
4.3.2	<i>Fourier Series (Robson, 1963)</i>	85
4.3.3	<i>Fourier Integrals (Robson, 1963, with permission)</i>	87
4.3.4	<i>Spectral Density (Robson, 1963)</i>	89

4.4	Numerical Integration Scheme for Frequency Content	91
4.4.1	<i>Introducing Discrete Fourier Transform (DFT)</i>	91
4.5	A Worked Example (Erzincan, 1992)	92
4.6	References	95
<b>5</b>	<b>Ground Motion Characteristics</b>	<b>97</b>
5.1	Characteristics of Ground Motion	97
5.1.1	<i>Ground Motion Particulars</i>	97
5.1.2	<i>After Shocks and Before Shocks</i>	99
5.1.3	<i>Earthquake Source Model</i>	103
5.1.4	<i>Empirical Relations of Source Parameters</i>	107
5.2	Ground Motion Parameters	110
5.2.1	<i>The Nature and Attenuation of Ground Motion</i>	114
5.2.2	<i>PGA and Modified Mercalli Intensity (MMI)</i>	114
5.2.3	<i>Engineering Models of Attenuation Relationships</i>	116
5.2.4	<i>Next Generation Attenuation (NGA) Models for Shallow Crustal Earthquakes in Western United States (2008)</i>	134
5.3	References	136
<b>6</b>	<b>Introduction to Response Spectra</b>	<b>141</b>
6.1	General Concepts	141
6.1.1	<i>A Designer's Perspective</i>	141
6.1.2	<i>A Practical Way Forward</i>	141
6.1.3	<i>Constructing Tripartite Plots</i>	145
6.2	Design Response Spectra	149
6.2.1	<i>A Worked Example: An MDOF System Subjected to Earthquake Loading</i>	152
6.3	Site Dependent Response Spectra	163
6.3.1	<i>The Design Process</i>	164
6.3.2	<i>Practical Example: Construction of a Site Dependent Response Spectrum</i>	166
6.4	Inelastic Response Spectra	174
6.4.1	<i>Response Spectra: A Cautionary Note</i>	176
6.5	References	178
<b>7</b>	<b>Probabilistic Seismic Hazard Analysis</b>	<b>181</b>
7.1	Introduction	181
7.1.1	<i>Seismic Hazard Analysis (SHA)</i>	183
7.1.2	<i>Features of PSHA</i>	183
7.2	Basic Steps in Probabilistic Seismic Hazard Analysis (PSHA)	183
7.2.1	<i>Historical Seismicity</i>	185
7.2.2	<i>Geology, Tectonics, Identification of Earthquake Source and the Geometry</i>	186
7.2.3	<i>Modelling Recurrence Laws</i>	186
7.2.4	<i>Gutenberg-Richter Recurrence Law</i>	186
7.2.5	<i>Alternative Models</i>	189

7.2.6	<i>Why the Gutenberg-Richter Model?</i>	189
7.2.7	<i>Ground Motion Parameter (peak acceleration, velocity etc.)</i>	190
7.2.8	<i>Local Soil Conditions</i>	190
7.2.9	<i>Temporal Model (or the arrival process)</i>	190
7.2.10	<i>Poisson Model</i>	191
7.3	Guide to Analytical Steps	192
7.3.1	<i>Multiple Point Sources</i>	192
7.3.2	<i>Area Source</i>	193
7.3.3	<i>Line Source</i>	194
7.4	PSHA as Introduced by Cornell	195
7.4.1	<i>Line Source Illustration Problem (Cornell, 1968)</i>	199
7.5	Monte Carlo Simulation Techniques	200
7.5.1	<i>Monte Carlo Simulation Process – An Insight</i>	203
7.5.2	<i>Example: Point Source (extracted from Cornell, 1968)</i>	204
7.6	Construction of Uniform Hazard Spectrum	207
7.6.1	<i>Monte Carlo Simulation Plots for Peak Ground Acceleration</i>	208
7.6.2	<i>Procedure for Construction of Uniform Hazard Response Spectrum</i>	209
7.6.3	<i>Further Attenuation Equations</i>	212
7.7	Further Computational Considerations	212
7.7.1	<i>De-aggregation – An Introduction</i>	212
7.7.2	<i>Computational Scheme for De-aggregation</i>	213
7.7.3	<i>Logic-Tree Simulation – An Introduction</i>	215
7.7.4	<i>Lest We Forget . . .</i>	216
7.8	References	216
<b>8</b>	<b>Code Provisions</b>	<b>219</b>
8.1	Introduction	219
8.1.1	<i>Historical Development</i>	221
8.2	Static Force Procedure	234
8.2.1	<i>Base Shear Method</i>	234
8.3	IBC 2006	239
8.3.1	<i>Introducing Mapped Spectral Accelerations</i>	239
8.3.2	<i>Dynamic Analysis Procedures</i>	239
8.4	Eurocode 8	244
8.4.1	<i>A Worked Example</i>	246
8.5	A Worked Example (IBC 2000)	249
8.5.1	<i>General</i>	249
8.5.2	<i>Design Criteria</i>	250
8.5.3	<i>Design Basis</i>	253
8.5.4	<i>Gravity Loads and Load Combinations</i>	253
8.5.5	<i>Gravity Load Analysis</i>	256
8.5.6	<i>Load Combinations For Design</i>	257
8.5.7	<i>Equivalent Lateral Force Procedure (1617.4)</i>	257
8.5.8	<i>Vertical Distribution of Base Shear (1617.4.3)</i>	258
8.5.9	<i>Lateral Analysis</i>	258

---

8.5.10	<i>Modification of Approximate Period</i>	259
8.5.11	<i>Revised Design Base Shear</i>	260
8.5.12	<i>Results of Analysis</i>	261
8.5.13	<i>Storey Drift Limitation</i>	261
8.5.14	<i>P – Δ Effects</i>	263
8.5.15	<i>Redundancy Factor, ρ, (1617.2)</i>	263
8.5.16	<i>Dynamic Analysis Procedure (response spectrum analysis)</i>	265
8.5.17	<i>Mode Shapes</i>	265
8.5.18	<i>Verification of Results from SAP 2000</i>	267
8.5.19	<i>L<sub>m</sub> and M<sub>m</sub> for each mode shape</i>	267
8.5.20	<i>Modal Seismic Design Coefficients, C<sub>sm</sub></i>	267
8.5.21	<i>Base Shear using Modal Analysis</i>	268
8.5.22	<i>Design Base Shear using Static Procedure</i>	269
8.5.23	<i>Scaling of Elastic Response Parameters for Design</i>	269
8.5.24	<i>Distribution of Base Shear</i>	270
8.5.25	<i>Lateral Analysis</i>	270
8.5.26	<i>Storey Drift Limitation</i>	275
8.5.27	<i>P – Δ Effects</i>	276
8.5.28	<i>Redundancy Factor, ρ</i>	276
8.6	References	276
<b>9</b>	<b>Inelastic Analysis and Design Concepts (with Particular Reference to H-Sections)</b>	<b>279</b>
9.1	Introduction	279
9.2	Behaviour of Beam Columns	280
9.2.1	<i>Short or Stocky Beam Column</i>	282
9.2.2	<i>Long or Intermediate Length Beam Column</i>	282
9.3	Full Scale Laboratory Tests	283
9.3.1	<i>Test Results</i>	285
9.3.2	<i>Mode of Failure</i>	285
9.3.3	<i>Experimental Plots</i>	286
9.4	Concepts and Issues: Frames Subjected to Seismic Loading	289
9.5	Proceeding with Dynamic Analysis (MDOF systems)	290
9.5.1	<i>Lateral Torsional Buckling</i>	291
9.5.2	<i>Column Strength Curves</i>	291
9.5.3	<i>Dynamic Analysis</i>	292
9.6	Behaviour of Steel Members under Cyclic Loading	293
9.6.1	<i>FE Analysis</i>	294
9.6.2	<i>A Note on Connections</i>	295
9.6.3	<i>A Note on the Factors Affecting the Strength of Columns</i>	295
9.7	Energy Dissipating Devices	296
9.7.1	<i>Introduction</i>	296
9.7.2	<i>Current Practice</i>	296
9.7.3	<i>Damping Devices in Use</i>	298
9.7.4	<i>Analytical Guidelines Currently Available</i>	303
9.8	References	303

<b>10 Soil-Structure Interaction Issues</b>	<b>305</b>
10.1 Introduction	305
10.2 Definition of the Problem	305
10.2.1 <i>Important Features of Soil-Structure Interaction</i>	306
10.2.2 <i>Ground Responses Observed During Earthquakes</i>	308
10.3 Damaging Effects due to Amplification	308
10.3.1 <i>Mexico City (1985) Earthquake</i>	308
10.3.2 <i>Loma Prieta (1989) Earthquake</i>	310
10.4 Damaging Effects Due to Liquefaction	316
10.4.1 <i>Design Implications for Piles due to Liquefaction</i>	320
10.5 References	321
<b>11 Liquefaction</b>	<b>323</b>
11.1 Definition and Description	323
11.1.1 <i>Geotechnical Aspects of Liquefaction</i>	323
11.2 Evaluation of Liquefaction Resistance	325
11.2.1 <i>Analytical Procedure – Empirical Formulation (Seed and Idriss, 1971)</i>	325
11.2.2 <i>A Simplified Method (Seed and Idriss, 1971)</i>	327
11.3 Liquefaction Analysis – Worked Example	332
11.3.1 <i>Problem Definition</i>	332
11.3.2 <i>Case Study – Using Field Data</i>	335
11.4 SPT Correlation for Assessing Liquefaction	338
11.4.1 <i>Current State of the Art</i>	338
11.4.2 <i>Most Recent Work</i>	344
11.4.3 <i>Worked Example with SPT Procedure (Idriss and Boulanger, 2004)</i>	346
11.5 Influence of Fines Content	348
11.6 Evaluation of Liquefaction Potential of Clay (cohesive) Soil	349
11.6.1 <i>Fresh Evidence of Liquefaction of Cohesive Soils</i>	349
11.7 Construction of Foundations of Structures in the Earthquake Zones Susceptible to Liquefaction	350
11.8 References	353
<b>12 Performance Based Seismic Engineering – An Introduction</b>	<b>357</b>
12.1 Preamble	357
12.2 Background to Current Developments	358
12.2.1 <i>Efforts in the USA</i>	359
12.2.2 <i>Efforts in Japan</i>	359
12.2.3 <i>Efforts in Europe</i>	360
12.3 Performance-Based Methodology	360
12.3.1 <i>Performance Objectives</i>	361
12.3.2 <i>Performance Levels</i>	362
12.3.3 <i>Performance Objectives</i>	363
12.3.4 <i>Hazard Levels (design ground motions)</i>	364

12.4	Current Analysis Procedures	365
12.4.1	<i>ATC Commentary</i>	367
12.4.2	<i>Displacement Design Procedures</i>	369
12.5	Second Generation Tools for PBSE	370
12.5.1	<i>Targets for 'Second Generation Tools'</i>	370
12.5.2	<i>Prognosis</i>	371
12.6	References	372
<b>Index</b>		<b>375</b>