

Table of Contents

Preface	xiii
Julien BAROTH, Franck SCHOEFS and Denys BREYSSE	
Introduction	xvii
Julien BAROTH, Alaa CHATEAUNEUF and Franck SCHOEFS	
PART 1. QUALITATIVE METHODS FOR EVALUATING THE RELIABILITY OF CIVIL ENGINEERING STRUCTURES	1
 Introduction to Part 1	3
 Chapter 1. Methods for System Analysis and Failure Analysis	5
Daniel BOISSIER, Laurent PEYRAS and Aurélie TALON	
1.1. Introduction	5
1.2. Structural analysis	7
1.2.1. The sub-systems	7
1.2.2. Environments	8
1.2.3. Bounding the analysis	8
1.2.4. Scales of a study	9
1.3. Functional analysis	10
1.3.1. Principles of functional analysis	10
1.3.2. External functional analysis	11
1.3.3. Internal functional analysis	12
1.4. Failure Modes and Effects Analysis (FMEA)	14
1.4.1. Principles of FMEA	14
1.4.2. Process FMEA	16
1.4.3. Product FMEA	17
1.5. Bibliography	19

Chapter 2. Methods for Modeling Failure Scenarios	21
Daniel BOISSIER, Laurent PEYRAS and Aurélie TALON	
2.1. Introduction	21
2.2. Event tree method	22
2.3. Fault tree method	24
2.3.1. Information acquisition	24
2.3.2. Fault tree construction	24
2.4. Bow-tie method	26
2.5. Criticality evaluation methods	29
2.5.1. Criticality formulation	30
2.5.2. Civil engineering considerations	34
2.6. Bibliography	34
Chapter 3. Application to a Hydraulic Civil Engineering Project	37
Daniel BOISSIER, Laurent PEYRAS and Aurélie TALON	
3.1. Context and approach for an operational reliability study	37
3.2. Functional analysis and failure mode analysis	39
3.2.1. Functional analysis of the system	39
3.2.2. Failure mode analysis, and effects	41
3.3. Construction of failure scenarios	42
3.4. Scenario criticality analysis	44
3.4.1. Hydrological study	44
3.4.2. Hydraulic model and quantitative consequence analysis	45
3.4.3. Evaluation of probability of technological failure	46
3.4.4. Representing the criticality of a scenario	49
3.5. Application summary	50
3.6. Bibliography	51
PART 2. HETEROGENEITY AND VARIABILITY OF MATERIALS: CONSEQUENCES FOR SAFETY AND RELIABILITY	53
Introduction to Part 2	55
Chapter 4. Uncertainties in Geotechnical Data	57
Denys BREYSSE, Julien BAROTH, Gilles CELEUX, Aurélie TALON and Daniel BOISSIER	
4.1. Various sources of uncertainty in geotechnical engineering	57
4.1.1. Erratic terrain, light disorder and anthropogenic terrain	58
4.1.2. Sources of uncertainty, errors, variability	58
4.1.3. Correlations between material properties	61
4.2. Erroneous, censored and sparse data	62
4.2.1. Erroneous data	62

4.2.2. Bounded data	63
4.2.3. Sparse data	63
4.3. Statistical representation of data	64
4.3.1. Notation	64
4.3.2. Spatial variability of material properties	66
4.4. Data modeling	66
4.4.1. Probabilistic and possibilistic approaches	67
4.4.2. Useful random variables (Gaussian, Weibull)	68
4.4.3. Maximum likelihood method	70
4.4.4. Example: resistance measurements in concrete samples	73
4.5. Conclusion	74
4.6. Bibliography	74
Chapter 5. Some Estimates on the Variability of Material Properties	77
Denys BREYSSE and Antoine MARACHE	
5.1. Introduction.	77
5.2. Mean value estimation	77
5.2.1. Sampling and estimation.	77
5.2.2. Number of data points required for an estimate	81
5.3. Estimation of characteristic values	82
5.3.1. Characteristic value and fractile of a distribution	82
5.3.2. Example: resistance measurements for wood samples	83
5.3.3. Optimization of number of useful tests	84
5.3.4. Estimate of <i>in situ</i> concrete mechanical strength	85
5.4. Principles of a geostatistical study	86
5.4.1. Geostatistical modeling tools	86
5.4.2. Estimation and simulation methods	90
5.4.3. Study of pressuremeter measurements in an urban environment	91
5.5. Bibliography	96
Chapter 6. Reliability of a Shallow Foundation Footing	97
Denys BREYSSE	
6.1. Introduction.	97
6.2. Bearing capacity models for strip foundations – modeling errors	98
6.3. Effects of soil variability on variability in bearing capacity and safety of the foundation.	101
6.3.1. Methodology	101
6.3.2. Purely frictional soil	104
6.3.3. Soil with friction and cohesion	106
6.4. Taking account of the structure of the spatial correlation and its influence on the safety of the foundation.	109
6.4.1. Spatial correlation and reduction in variance.	109

6.4.2. Taking account of the spatial correlation, and results	112
6.5. Conclusions	115
6.5.1. Conclusions drawn from case study	115
6.5.2. General conclusions	116
6.6. Bibliography	117
PART 3. METAMODELS FOR STRUCTURAL RELIABILITY	119
Introduction to Part 3	121
Chapter 7. Physical and Polynomial Response Surfaces	123
Frédéric DUPRAT, Franck SCHOEFS and Bruno SUDRET	
7.1. Introduction	123
7.2. Background to the response surface method	124
7.3. Concept of a response surface	125
7.3.1. Basic definitions	125
7.3.2. Various formulations	126
7.3.3. Building criteria	127
7.4. Usual reliability methods	131
7.4.1. Reliability issues and Monte Carlo simulation	131
7.4.2. FORM	131
7.5. Polynomial response surfaces	133
7.5.1. Basic formulation	133
7.5.2. Working space	135
7.5.3. Response surface expression	135
7.5.4. Building the numerical experimental design	136
7.5.5. Example of an adaptive RS method	138
7.6. Conclusion	143
7.7. Bibliography	143
Chapter 8. Response Surfaces based on Polynomial Chaos Expansions . .	147
Bruno SUDRET, Géraud BLATMAN and Marc BERVEILLER	
8.1. Introduction	147
8.1.1. Statement of the reliability problem	147
8.1.2. From Monte Carlo simulation to polynomial chaos expansions . .	148
8.2. Building of a polynomial chaos basis	149
8.2.1. Orthogonal polynomials	149
8.2.2. Example	150
8.3. Computation of the expansion coefficients	151
8.3.1. Introduction	151
8.3.2. Projection methods	153
8.3.3. Regression methods	154

8.3.4. Post-processing of the coefficients	157
8.4. Applications in structural reliability	158
8.4.1. Elastic engineering truss	158
8.4.2. Frame structure	161
8.5. Conclusion	164
8.6. Bibliography	165
PART 4. METHODS FOR STRUCTURAL RELIABILITY OVER TIME	169
Introduction to Part 4	171
Chapter 9. Data Aggregation and Unification	173
Daniel BOISSIER and Aurélie TALON	
9.1. Introduction	173
9.2. Methods of data aggregation and unification	173
9.2.1. Data unification methods	175
9.2.2. Data aggregation methods	179
9.3. Evaluation of evacuation time for an apartment in case of fire	181
9.4. Conclusion	185
9.5. Bibliography	185
Chapter 10. Time-Variant Reliability Problems	187
Bruno SUDRET	
10.1. Introduction	187
10.2. Random processes	188
10.2.1. Definition and elementary properties	188
10.2.2. Gaussian random processes	190
10.2.3. Poisson and rectangular wave renewal processes	190
10.3. Time-variant reliability problems	192
10.3.1. Problem statement	192
10.3.2. Right-boundary problems	193
10.3.3. General case	194
10.4. PHI2 method	197
10.4.1. Implementation of the PHI2 method – stationary case	198
10.4.2. Implementation of the PHI2 method – non-stationary case	200
10.4.3. Semi-analytical example	200
10.5. Industrial application: truss structure under time-varying loads	202
10.6. Conclusion	204
10.7. Bibliography	205

Chapter 11. Bayesian Inference and Markov Chain Monte Carlo Methods	207
Gilles CELEUX	
11.1. Introduction	207
11.2. Bayesian Inference	208
11.2.1. Bayesian estimation of the mean of a Gaussian distribution	209
11.3. MCMC methods for weakly informative data.	210
11.3.1. Weakly informative statistical problems	210
11.3.2. From prior information to prior distributions.	211
11.3.3. Approximating a posterior distribution	212
11.3.4. A popular MCMC method: Gibbs sampling	213
11.3.5. Metropolis–Hastings algorithm	214
11.3.6. Assessing the convergence of an MCMC algorithm.	217
11.3.7. Importance sampling	218
11.4. Estimating a competing risk model from censored and incomplete data	219
11.4.1. Choosing the prior distributions	220
11.4.2. From prior information to prior hyperparameters	221
11.4.3. Gibbs sampling	221
11.4.4. Adaptive Importance Sampling (AIS)	222
11.5. Conclusion	225
11.6. Bibliography	225
Chapter 12. Bayesian Updating Techniques in Structural Reliability	227
Bruno SUDRET	
12.1. Introduction	227
12.2. Problem statement: link between measurements and model prediction	228
12.3. Computing and updating the failure probability	229
12.3.1. Structural reliability – problem statement.	229
12.3.2. Updating failure probability	232
12.4. Updating a confidence interval on response quantities.	233
12.4.1. Quantiles as the solution of an inverse reliability problem.	233
12.4.2. Updating quantiles of the response quantity	234
12.4.3. Conclusion	234
12.5. Bayesian updating of the model basic variables	235
12.5.1. A reminder of Bayesian statistics.	235
12.5.2. Bayesian updating of the model basic variables	235
12.6. Updating the prediction of creep strains in containment vessels of nuclear power plants	238
12.6.1. Industrial problem statement	238
12.6.2. Deterministic models	239

12.6.3. Prior and posterior estimations of the delayed strains	242
12.7. Conclusion	245
12.8. Acknowledgments	246
12.9. Bibliography	246
PART 5. RELIABILITY-BASED MAINTENANCE OPTIMIZATION	249
Introduction to Part 5	251
Chapter 13. Maintenance Policies	253
Alaa CHATEAUNEUF, Franck SCHOEFS and Bruno CAPRA	
13.1. Maintenance	253
13.1.1. Lifetime distribution	253
13.1.2. Maintenance cycle	254
13.1.3. Maintenance planning	255
13.2. Types of maintenance	257
13.2.1. Choice of the maintenance policy	257
13.2.2. Maintenance program	260
13.2.3. Inspection program	261
13.3. Maintenance models	262
13.3.1. Model of perfect maintenance: AGAN	263
13.3.2. Model of minimal maintenance: ABAO	264
13.3.3. Model of imperfect or bad maintenance: BTO/WTO	265
13.3.4. Complex maintenance policy	267
13.4. Conclusion	269
13.5. Bibliography	269
Chapter 14. Maintenance Cost Models	271
Alaa CHATEAUNEUF and Franck SCHOEFS	
14.1. Preventive maintenance	271
14.2. Maintenance based on time	273
14.2.1. Model I	274
14.2.2. Model II	274
14.2.3. Model III	275
14.3. Maintenance based on age	275
14.4. Inspection models	276
14.4.1. Impact of inspection on costs	276
14.4.2. The case of imperfect inspections	277
14.5. Structures with large lifetimes	283
14.6. Criteria for choosing a maintenance policy	284
14.7. Example of a corroded steel pipeline	285
14.8. Conclusion	290
14.9. Bibliography	290

Chapter 15. Practical Aspects: Industrial Implementation and Limitations in a Multi-criteria Context	293
Franck SCHOEFS and Bruno CAPRA	
15.1. Introduction	293
15.2. Motorway concession with high performance requirements	296
15.2.1. Background and stakes	296
15.2.2. Methodology	298
15.2.3. Results	300
15.3. Ageing of civil engineering structures: using field data to update predictions	303
15.3.1. Background and stakes	303
15.3.2. Corrosion risk of a cooling tower	303
15.3.3. Bayesian updating	305
15.4. Conclusion	307
15.5. Bibliography	308
Conclusion	311
Julien BAROTH, Franck SCHOEFS and Denys BREYSSE	
List of Symbols	315
List of Authors	323
Index	325