

Contents

Introduction	11
Acknowledgements	13
List of symbols	15
1 Waves and vibrations in soils	19
1.1 Various fields and applications	19
1.2 Vibrations due to construction works	20
1.2.1 Pile driving	20
1.2.2 Dynamic compaction	24
1.2.3 Vibratory compaction	28
1.3 Vibrations induced by wind turbines	31
1.4 Blast induced vibrations	33
1.4.1 Vibrations induced in mines	33
1.4.2 Vibrations induced in quarries	34
1.5 Traffic induced vibrations	36
1.5.1 Vibrations due to road traffic	36
1.5.2 Vibrations due to railways	39
1.5.3 Theoretical analysis of moving loads	40
1.6 Vibration isolation	42
1.6.1 Practical problem	42
1.6.2 Experimental results	42
1.6.3 Numerical models	44
1.6.4 Values of the mechanical parameters	48
1.7 Earthquake engineering and seismology	49
1.7.1 Analysis at various scales	49
1.7.2 Seismic wave propagation in soils	50
1.7.3 Values of the mechanical parameters	51
1.8 Synthesis of the various parameters	52

2	1D-wave propagation	53
2.1	Introduction	53
2.2	Dynamic equilibrium of a beam	53
2.2.1	Kinematics and main assumptions	53
2.2.2	Virtual rate of work by internal forces	54
2.2.3	Virtual rate of work by external forces	56
2.2.4	Virtual rate of work by quantities of acceleration	57
2.2.5	Equilibrium equation	57
2.3	Longitudinal vibrations of beams	59
2.3.1	Dynamic equilibrium	59
2.3.2	Homogeneous equation	60
2.3.3	Solution in terms of stresses	62
2.3.4	Eigenmodes of the bar	62
2.3.5	Example 1: pile driving	64
2.3.6	Example 2: characterization of a heterogeneous bar	68
2.3.7	Absorbing boundaries	70
2.4	Torsional vibrations of beams	71
2.4.1	Dynamic equilibrium	71
2.4.2	Homogeneous equation	72
2.4.3	Stresses in the beam	73
2.4.4	Eigenmodes of the beam	73
2.5	Shear vibrations of beams	75
2.5.1	Bending-shear vibrations	75
2.5.2	From bending-shear to pure shear	75
2.6	Behaviour of dissipative media	76
2.6.1	Dissipative phenomena	76
2.6.2	Viscoelastic behaviour	76
2.6.3	Rheological models	79
2.7	Wave propagation in viscoelastic media	84
2.7.1	Dynamic equilibrium	84
2.7.2	Viscoelastic behaviour	84
2.7.3	Wave equation in viscoelastic media	85
2.7.4	Complex wavenumber	85
2.7.5	Relationship between α and Q^{-1}	86
2.7.6	Dispersion laws	87
2.8	Examples of propagation in viscoelastic media	88
2.8.1	Example 1 : propagation of a triangular signal	88
2.8.2	Example 2 : propagation of a seismic wave.	91
2.9	Other linear and nonlinear models	91
2.9.1	Constant Q (CQ) model	91
2.9.2	Frequency dependent Q model	92
2.9.3	Nearly Constant Q (NCQ) model	92
2.9.4	Equivalent linear viscoelasticity	94
2.9.5	Frequency dependent models	95
2.9.6	Nonlinear viscoelastic models	96

2.10	Application 1: dynamic characterization on resonant column	97
2.10.1	Principles of the test	97
2.10.2	Description of the specimen motion	98
2.10.3	Actual resonant column test	99
2.10.4	Estimation of damping	101
2.10.5	Results from resonant column tests	102
2.11	Application 2: dynamic characterization under fast loadings	103
2.11.1	Split Hopkinson Pressure Bar test	103
2.11.2	Experimental device	104
2.11.3	Stress wave in the specimen	104
2.11.4	Determination of the mechanical parameters	106
2.11.5	3D Split Hopkinson Pressure Bar test	108
2.11.6	3D fast dynamic response of sand	110
2.12	Application 3: response of a heterogeneous soil profile	112
2.12.1	Soil behaviour	112
2.12.2	Wave equation for a heterogeneous profile	113
2.12.3	Boundary conditions	114
2.12.4	Eigenfrequencies and mode participation factors	118
2.13	Application 4: soil-structure interaction	119
2.13.1	Basic principles	119
2.13.2	Equations of motion for the soil	120
2.13.3	Case of a surface excitation	120
2.13.4	Influence of the wave velocity in the soil	122
2.14	Experimental estimation of damping	122
2.14.1	Various experimental methods	122
2.14.2	Methods for the estimation of attenuation	124
2.14.3	Definitions of attenuation: synthesis	125
2.14.4	Variations of attenuation	126
2.14.5	Characterization of the various approaches	127
2.14.6	Comparison of the governing parameters	127
3	2D/3D-wave propagation	131
3.1	Introduction	131
3.2	Dynamic equilibrium of a continuous medium	131
3.2.1	Equilibrium equation - principle of virtual work	132
3.2.2	Constitutive equation	133
3.2.3	Equilibrium equations in terms of displacements	134
3.2.4	Decomposition of the displacement field	134
3.2.5	Uncoupled wave equations	135
3.2.6	Body waves	135
3.2.7	Wave propagation in anisotropic media	137
3.3	Wave propagation in unbounded media	138
3.3.1	Wave equations for plane waves	138
3.3.2	Plane monochromatic waves	140
3.3.3	Reflection-refraction of plane waves at an interface	142

3.3.4	Plane waves in layered media: vibration isolation	152
3.4	Spherical waves	174
3.4.1	Wave equation	174
3.4.2	Solution wavefield	174
3.4.3	Geometrical damping	175
3.5	Waves in a homogeneous or heterogeneous half-space	176
3.5.1	Surface waves: <i>SH</i> case	176
3.5.2	Surface waves: <i>P/SV</i> case	177
3.5.3	Propagation of a plane <i>SH</i> -wave in a surface layer	180
3.5.4	Amplification of seismic waves in layered media	186
3.6	Application 1: waves in centrifuged models	188
3.6.1	Historical summary	188
3.6.2	Equivalence principle	188
3.6.3	Calculation of the scaling factors	189
3.6.4	Dynamic experiments in the centrifuge	190
3.6.5	Examples of dynamic centrifuge experiments	192
3.6.6	Analysis of the three-dimensional wavefield	194
3.6.7	Modelling propagation in dissipative soils	196
3.6.8	Simulations for drop-ball experiments	199
3.6.9	Influence of frequency on attenuation factor	203
3.6.10	Numerical modelling of centrifuge experiments	204
3.6.11	Removing reflections by homomorphic filtering	206
3.6.12	Analysis of dispersion	207
3.7	Application 2: Spectral Analysis of Surface Waves and in situ tests	208
3.7.1	Dispersion of Love waves in a single-layered half-space	208
3.7.2	Dispersion of surface waves in a heterogeneous half-space	214
3.7.3	Steady State Rayleigh method	218
3.7.4	Spectral Analysis of Surface Waves: experiments	218
3.7.5	Seismic refraction	224
3.7.6	In-hole tests	226
3.7.7	Microtremor methods	235
3.7.8	Conclusions on field tests	236
4	Modelling wave propagation	239
4.1	Numerical methods for wave propagation	239
4.1.1	Modelling wave propagation	239
4.1.2	Numerical Modelling in Elastodynamics	240
4.1.3	Time domain vs frequency domain	240
4.1.4	Actual or synthetic signals	241
4.2	The Finite Element Method	246
4.2.1	Strong formulation	246
4.2.2	Weak formulation	247
4.2.3	Approximate minimization: Galerkin method	248
4.2.4	Finite elements	248
4.2.5	Time integration algorithms	253

4.2.6	Spectral elements	255
4.3	Numerical dispersion	257
4.3.1	Physical dispersion and attenuation	257
4.3.2	Numerical errors for wave propagation	258
4.3.3	Theoretical numerical dispersion	260
4.3.4	Time-step estimates for some simple cases	264
4.3.5	Numerical dispersion for low order elements	264
4.3.6	Influence of the geometrical arrangement	265
4.3.7	Influence of mass matrix formulation	268
4.3.8	Efficiency of higher order elements	269
4.4	Physical and numerical damping	275
4.4.1	Rayleigh and Caughey damping	275
4.4.2	Rheological interpretation of Rayleigh damping	276
4.4.3	Attenuation models for geomaterials	277
4.4.4	Numerical damping	281
4.5	Modelling wave propagation in unbounded media	283
4.5.1	Absorbing boundaries in 1D	283
4.5.2	Absorbing boundaries in 2D	284
4.5.3	Infinite elements	286
4.5.4	Absorbing layers (PML)	289
4.5.5	Coupled approaches	296
4.6	The Boundary Element Method	298
4.6.1	Interest of the method in dynamics	298
4.6.2	Maxwell-Betti theorem	298
4.6.3	Integral equations in elastodynamics	298
4.6.4	Discretization and regularization principle	301
4.6.5	Wave propagation in unbounded media	302
4.6.6	Numerical Implementation	303
4.6.7	Validation and influence of the regularization	304
4.6.8	Advanced formulation: the Fast Multipole Method	306
4.6.9	Elastodynamics in time domain	308
4.7	Applications to wave propagation in soil	308
4.7.1	Diffraction of a plane wave in unbounded media	308
4.7.2	Vibrations of a foundation	312
4.7.3	Vibration isolation using piles or trenches	313
4.7.4	Traffic induced vibrations in railway tunnels	321
5	Seismic wave propagation and amplification	323
5.1	Introduction	323
5.2	Seismic wave amplification	324
5.2.1	Main governing phenomena	324
5.2.2	Experimental characterization	327
5.3	Seismic wave amplification in layered media	328
5.3.1	From transfer function to time-domain response	328
5.3.2	Amplification in single-layered media	330

5.3.3	Amplification in multi-layered media	333
5.4	Amplification due to the topography	333
5.4.1	Main phenomena and simplified analysis	333
5.4.2	Amplification by crests and hills	336
5.4.3	Amplification by canyons	340
5.4.4	Amplification on actual topographies	345
5.5	Amplification of seismic waves in 2D alluvial basins	351
5.5.1	Amplification by wedges	351
5.5.2	Theoretical basins	356
5.5.3	Cylindrical basins	361
5.5.4	Cylindrical basin vs horizontally layered soil	362
5.5.5	Elliptical basins with variable shape ratio	365
5.5.6	2D/1D aggravation factor	366
5.6	Amplification of seismic waves in 3D alluvial basins	367
5.6.1	Semi-spherical basin	367
5.6.2	Sine-shaped basin	369
5.6.3	Semi-spherical basin and oblique incidences	370
5.6.4	Semi-ellipsoidal basin	372
5.6.5	Moon-valley model	372
5.7	Modal approaches to analyze site effects	374
5.7.1	Amplification of the seismic motion and resonance	374
5.7.2	Various types of modal approaches	374
5.7.3	Simplified modal method	375
5.7.4	Features of the various modal methods	376
5.7.5	Fundamental frequency of a geological structure	376
5.7.6	Modal estimation of the fundamental frequency	378
5.7.7	Simplified modal method vs experimental spectral ratios	379
5.8	Amplification in shallow basins (e.g. Nice)	380
5.8.1	Analysis of site effects in Nice (France)	380
5.8.2	Amplification from 1D transfer functions	382
5.8.3	2D model of the geological profile	383
5.8.4	Amplification of a plane <i>SH</i> -wave	384
5.8.5	Influence of attenuation	386
5.8.6	1D and 2D amplification vs experimental results	387
5.8.7	2D/1D aggravation factor	388
5.8.8	Comparison with the simplified modal method	389
5.8.9	Time-domain simulations	390
5.8.10	Comparisons with a deep alluvial basin	390
5.9	Amplification in a deep basin (Volvi)	393
5.9.1	The Volvi EuroSeisTest	393
5.9.2	Simplified and complete models of the Volvi basin	396
5.9.3	<i>SH</i> wave amplification in the Volvi basin	397
5.9.4	Comparisons between simplified and complete models	400
5.9.5	<i>SV</i> -wave amplification in the Volvi basin	406
5.9.6	2D/1D aggravation factor	406

5.9.7	Conclusions on site effects in Volvi	408
5.10	Wave-structure interaction	410
5.10.1	From soil-structure to wave-structure interaction	410
5.10.2	Seismic analysis for buildings	410
5.10.3	Seismic interaction with underground structures	412
5.10.4	Seismic interactions at the local and global scales	413
Appendices		419
A Several operators in mechanics		419
A.1	Vectors and product of vectors	419
A.2	Tensors and product	419
A.3	Gradient and Laplacian	419
A.3.1	Definitions	419
A.3.2	Examples	420
B Synthetic wavelets		421
B.1	Ricker wavelet	421
B.2	Gabor wavelet	424
B.3	Mavroeidis & Papageorgiou wavelet	425
B.4	Generalized Rayleigh wavelet	426
B.5	Küpper wavelet	427
B.6	Ormsby wavelet	428
B.7	Morlet wavelet	429
B.8	Meyer wavelet	430
B.9	Double- M wavelet	432
C Spectral analysis and filtering		433
C.1	Fourier transform	433
C.1.1	Definitions	433
C.1.2	Main properties	434
C.1.3	Usual transforms	434
C.1.4	Fourier transforms of synthetic wavelets	435
C.1.5	Wave propagation in viscoelastic media	435
C.1.6	Fourier transforms of actual signals	438
C.2	Filtering	439
C.2.1	Classical filters	439
C.2.2	Filtered signals: examples	439
C.3	Hilbert transform and envelope curve	440
C.3.1	Definition	440
C.3.2	Envelope curves	441

D Propagating waves: duration, velocity, echoes	443
D.1 From acceleration to displacement	443
D.1.1 Integration of accelerograms	443
D.1.2 Baseline correction	443
D.1.3 Spectral methods	443
D.2 PGA, PGV, PGD	444
D.3 Signal duration	445
D.4 Estimation of wave velocity	447
D.4.1 Peak to peak estimation	447
D.4.2 Cross-correlation function	448
D.5 Detection of reflected waves and echoes	449
D.5.1 Autocorrelation function	449
D.5.2 Real cepstrum	449
D.5.3 Time phase	449
E Echo removal by homomorphic filtering	451
E.1 Basic principles	451
E.2 Computation of the complex cepstrum	451
E.3 Removing echoes thanks to cepstral filtering	453
E.3.1 Principle of the method	453
E.3.2 Homomorphic filtering: summary	453
E.3.3 Application to actual measurements	454
References	459
Index	493