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Elastic Wave Propagation and Generation in Seismology

Seismology has complementary observational and theoretical components, and a thorough understanding of the observations requires a sound theoretical background. Seismological theory, however, can be a difficult mathematical subject and introductory books do not generally give students the tools they need to solve seismological problems by themselves. This book addresses these shortcomings by bridging the gap between introductory textbooks and advanced monographs. It provides the necessary mathematical machinery and demonstrates how to apply it.

The author's approach is to consider seismological phenomena as problems in applied mathematics. To this end, each problem is carefully formulated and its solution is derived in a step-by-step approach. Although some exposure to vector calculus and partial differential equations is expected, most of the mathematics needed is derived within the book. This includes Cartesian tensors, solution of 3-D scalar and vector wave equations, Green's functions, and continuum mechanics concepts. The book covers strain, stress, propagation of body and surface waves in simple models (half-spaces and the layer over a half-space), ray theory for P and S waves (including amplitude equations), near and far fields generated by moment tensor sources in infinite media, and attenuation and the mathematics of causality.

Numerous programs for the computation of reflection and transmission coefficients, for the generation of P- and S-wave radiation patterns, and for near- and far-field synthetic seismograms in infinite media are provided by the author on a dedicated website. The book also includes problems for students to work through, with solutions available on the associated website. This book will therefore find a receptive audience among advanced undergraduate and graduate students interested in developing a solid mathematical background to tackle more advanced topics in seismology. It will also form a useful reference volume for researchers wishing to brush up on the fundamentals.

JOSE PUJOL received a B.S. in Chemistry, from the Universidad Nacional del Sur, Bahia Blanca, Argentina, in 1968 and then went on to graduate studies in quantum chemistry at Uppsala University, Sweden, and Karlsruhe University, Germany. Following further graduate studies in petroleum exploration at the University of Buenos Aires, Argentina, he studied for an M.S. in geophysics, at the University of Alaska (1982) and a Ph.D. at the University of Wyoming (1985). He has been a faculty member at the University of Memphis since 1985 where he is currently an Associate Professor in the Center for Earthquake Research and Information. Professor Pujol's research interests include earthquake and exploration seismology, vertical seismic profiling, inverse problems, earthquake location and velocity inversion, and attenuation studies using borehole data. He is also an associate editor for the Seismological Society of America.

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> In memory of my father Jose A. Pujol

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Contents

	Preface p			<i>ige</i> xiii	
	Ackr	nowledgements		xviii	
1	Intr	oduction to tensors and dyadics		1	
	1.1	Introduction		1	
	1.2	Summary of vector analysis		2	
	1.3	Rotation of Cartesian coordinates. Definiti	on of a vector	7	
	1.4	Cartesian tensors			
		1.4.1 Tensor operations		14	
		1.4.2 Symmetric and anti-symmetric ten	sors	16	
		1.4.3 Differentiation of tensors		17	
		1.4.4 The permutation symbol		18	
		1.4.5 Applications and examples		19	
		1.4.6 Diagonalization of a symmetric sec	cond-order tensor	23	
		1.4.7 Isotropic tensors		28	
		1.4.8 Vector associated with a second-or	der anti-symmetric		
		tensor		28	
		1.4.9 Divergence or Gauss' theorem		29	
	1.5	Infinitesimal rotations		30	
	1.6	Dyads and dyadics		32	
		1.6.1 Dyads		33	
		1.6.2 Dyadics		34	
2	Defo	ormation. Strain and rotation tensors		40	
	2.1	Introduction		40	
	2.2	Description of motion. Lagrangian and Eu	lerian points of view	41	
	2.3	Finite strain tensors		43	
	2.4	The infinitesimal strain tensor		45	

...

viii		Contents	
		2.4.1 Geometric meaning of ε_{ii}	46
		2.4.2 Proof that ε_{ii} is a tensor	49
	2.5	The rotation tensor	50
	2.6	Dyadic form of the strain and rotation tensors	51
	2.7	Examples of simple strain fields	52
3	The s	stress tensor	59
	3.1	Introduction	59
	3.2	Additional continuum mechanics concepts	59
		3.2.1 Example	63
	3.3	The stress vector	64
	3.4	The stress tensor	67
	3.5	The equation of motion. Symmetry of the stress tensor	70
	3.6	Principal directions of stress	72
	3.7	Isotropic and deviatoric components of the stress tensor	72
	3.8	Normal and shearing stress vectors	73
	3.9	Stationary values and directions of the normal and shearing	
		stress vectors	75
	3.10	Mohr's circles for stress	79
4	Line	ar elasticity – the elastic wave equation	84
	4.1	Introduction	84
	4.1 4.2	Introduction The equation of motion under the small-deformation	84
	4.1 4.2	Introduction The equation of motion under the small-deformation approximation	84 85
	4.14.24.3	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations	84 85 86
	4.14.24.34.4	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations Strain energy	84 85 86 88
	 4.1 4.2 4.3 4.4 4.5 	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations Strain energy Linear elastic and hyperelastic deformations	84 85 86 88 90
	 4.1 4.2 4.3 4.4 4.5 4.6 	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations Strain energy Linear elastic and hyperelastic deformations Isotropic elastic solids	84 85 86 88 90 92
	 4.1 4.2 4.3 4.4 4.5 4.6 4.7 	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations Strain energy Linear elastic and hyperelastic deformations Isotropic elastic solids Strain energy density for the isotropic elastic solid	84 85 86 88 90 92 96
	4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations Strain energy Linear elastic and hyperelastic deformations Isotropic elastic solids Strain energy density for the isotropic elastic solid The elastic wave equation for a homogeneous isotropic medium	 84 85 86 88 90 92 96 97
5	4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 Scala	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations Strain energy Linear elastic and hyperelastic deformations Isotropic elastic solids Strain energy density for the isotropic elastic solid The elastic wave equation for a homogeneous isotropic medium ur and elastic waves in unbounded media	 84 85 86 88 90 92 96 97 100
5	4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 Scala 5.1	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations Strain energy Linear elastic and hyperelastic deformations Isotropic elastic solids Strain energy density for the isotropic elastic solid The elastic wave equation for a homogeneous isotropic medium ir and elastic waves in unbounded media Introduction	84 85 86 88 90 92 96 97 100 100
5	4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 Scala 5.1 5.2	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations Strain energy Linear elastic and hyperelastic deformations Isotropic elastic solids Strain energy density for the isotropic elastic solid The elastic wave equation for a homogeneous isotropic medium ur and elastic waves in unbounded media Introduction The 1-D scalar wave equation	84 85 86 88 90 92 96 97 100 100
5	4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 Scala 5.1 5.2	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations Strain energy Linear elastic and hyperelastic deformations Isotropic elastic solids Strain energy density for the isotropic elastic solid The elastic wave equation for a homogeneous isotropic medium ar and elastic waves in unbounded media Introduction The 1-D scalar wave equation 5.2.1 Example	84 85 86 88 90 92 96 97 100 100 100
5	4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 Scala 5.1 5.2 5.3	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations Strain energy Linear elastic and hyperelastic deformations Isotropic elastic solids Strain energy density for the isotropic elastic solid The elastic wave equation for a homogeneous isotropic medium ar and elastic waves in unbounded media Introduction The 1-D scalar wave equation 5.2.1 Example The 3-D scalar wave equation	 84 85 86 88 90 92 96 97 100 100 103 103
5	4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 Scala 5.1 5.2 5.3 5.4	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations Strain energy Linear elastic and hyperelastic deformations Isotropic elastic solids Strain energy density for the isotropic elastic solid The elastic wave equation for a homogeneous isotropic medium ar and elastic waves in unbounded media Introduction The 1-D scalar wave equation 5.2.1 Example The 3-D scalar wave equation Plane harmonic waves. Superposition principle	84 85 86 88 90 92 96 97 100 100 100 103 103
5	4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 Scala 5.1 5.2 5.3 5.4 5.5	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations Strain energy Linear elastic and hyperelastic deformations Isotropic elastic solids Strain energy density for the isotropic elastic solid The elastic wave equation for a homogeneous isotropic medium ar and elastic waves in unbounded media Introduction The 1-D scalar wave equation 5.2.1 Example The 3-D scalar wave equation Plane harmonic waves. Superposition principle Spherical waves	84 85 86 88 90 92 96 97 100 100 100 103 103 107 111
5	4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 Scala 5.1 5.2 5.3 5.4 5.5 5.6	Introduction The equation of motion under the small-deformation approximation Thermodynamical considerations Strain energy Linear elastic and hyperelastic deformations Isotropic elastic solids Strain energy density for the isotropic elastic solid The elastic wave equation for a homogeneous isotropic medium ar and elastic waves in unbounded media Introduction The 1-D scalar wave equation 5.2.1 Example The 3-D scalar wave equation Plane harmonic waves. Superposition principle Spherical waves Vector wave equation. Vector solutions	 84 85 86 88 90 92 96 97 100 100 100 103 103 107 111 112

		Contents	ix
		5.6.2 Harmonic potentials	116
	5.7	Vector Helmholtz equation	116
	5.8	Elastic wave equation without body forces	117
		5.8.1 Vector <i>P</i> - and <i>S</i> -wave motion	118
		5.8.2 Hansen vectors for the elastic wave equation in the	
		frequency domain	119
		5.8.3 Harmonic elastic plane waves	121
		5.8.4 <i>P</i> -, <i>SV</i> -, and <i>SH</i> -wave displacements	123
	5.9	Flux of energy in harmonic waves	125
6	Plan	e waves in simple models with plane boundaries	129
	6.1	Introduction	129
	6.2	Displacements	131
	6.3	Boundary conditions	134
	6.4	Stress vector	135
	6.5	Waves incident at a free surface	136
		6.5.1 Incident SH waves	136
		6.5.2 Incident <i>P</i> waves	137
		6.5.3 Incident SV waves	144
	6.6	Waves incident on a solid-solid boundary	152
		6.6.1 Incident SH waves	152
		6.6.2 Incident <i>P</i> waves	157
		6.6.3 Incident SV waves	164
	6.7	Waves incident on a solid-liquid boundary	168
		6.7.1 Incident <i>P</i> waves	168
		6.7.2 Incident SV waves	169
	6.8	P waves incident on a liquid-solid boundary	169
	6.9	Solid layer over a solid half-space	170
		6.9.1 Incident SH waves	172
		6.9.2 Incident <i>P</i> and <i>SV</i> waves	179
7	Surf	ace waves in simple models – dispersive waves	188
	7.1	Introduction	188
	7.2	Displacements	189
	7.3	Love waves	191
		7.3.1 Homogeneous half-space	191
		7.3.2 Layer over a half-space	191
		7.3.3 Love waves as the result of constructive interference	198
		7.3.4 Vertically heterogeneous medium	199
	7.4	Rayleigh waves	202

х	Contents			
		7.4.1	Homogeneous half-space	202
		7.4.2	Layer over a half-space. Dispersive Rayleigh waves	206
		7.4.3	Vertically heterogeneous medium	209
	7.5	Stone	ley waves	212
	7.6	Propa	gation of dispersive waves	213
		7.6.1	Introductory example. The dispersive string	214
		7.6.2	Narrow-band waves. Phase and group velocity	215
		7.6.3	Broad-band waves. The method of stationary phase	220
		7.6.4	The Airy phase	227
8	Ray	theory		234
	8.1	Introd	uction	234
	8.2	Ray th	neory for the 3-D scalar wave equation	235
	8.3	Ray th	neory for the elastic wave equation	237
		8.3.1	P and S waves in isotropic media	240
	8.4	Wave	fronts and rays	242
		8.4.1	Medium with constant velocity	244
		8.4.2	Medium with a depth-dependent velocity	246
		8.4.3	Medium with spherical symmetry	247
	8.5	Differ	ential geometry of rays	248
	8.6	Calcul	lus of variations. Fermat's principle	254
	8.7	Ray a	mplitudes	258
		8.7.1	Scalar wave equation	258
		8.7.2	Elastic wave equation	261
		8.7.3	Effect of discontinuities in the elastic parameters	268
	8.8	Exam	ples	269
		8.8.1	SH waves in a layer over a half-space at normal	
			incidence	270
		8.8.2	Ray theory synthetic seismograms	274
9	Seis	mic poi	nt sources in unbounded homogeneous media	278
	9.1	Introd	uction	278
	9.2	The so	calar wave equation with a source term	279
	9.3	Helml	noltz decomposition of a vector field	281
	9.4	Lamé	's solution of the elastic wave equation	282
	9.5	The el	lastic wave equation with a concentrated force in the x_j	
		directi	on	285
		9.5.1	Type of motion	288
		9.5.2	Near and far fields	289

	Contents		xi
		9.5.3 Example. The far field of a point force at the origin in	
		the x_3 direction	291
	9.6	Green's function for the elastic wave equation	295
	9.7	The elastic wave equation with a concentrated force in an	
		arbitrary direction	296
	9.8	Concentrated couples and dipoles	297
	9.9	Moment tensor sources. The far field	300
		9.9.1 Radiation patterns. SV and SH waves	303
	9.10	Equivalence of a double couple and a pair of compressional	
		and tensional dipoles	305
	9.11	The tension and compression axes	306
	9.12	Radiation patterns for the single couple M_{31} and the double	
		couple $M_{13} + M_{31}$	308
	9.13	Moment tensor sources. The total field	311
		9.13.1 Radiation patterns	313
10	The	earthquake source in unbounded media	316
	10.1	Introduction	316
	10.2	A representation theorem	318
	10.3	Gauss' theorem in the presence of a surface of discontinuity	321
	10.4	The body force equivalent to slip on a fault	322
	10.5	Slip on a horizontal plane. Point-source approximation. The	
		double couple	325
	10.6	The seismic moment tensor	329
	10.7	Moment tensor for slip on a fault of arbitrary orientation	331
	10.8	Relations between the parameters of the conjugate planes	338
	10.9	Radiation patterns and focal mechanisms	339
	10.10) The total field. Static displacement	347
	10.11	Ray theory for the far field	352
11	Anel	astic attenuation	357
	11.1	Introduction	357
	11.2	Harmonic motion. Free and damped oscillations	360
		11.2.1 Temporal O	362
	11.3	The string in a viscous medium	364
	11.4	The scalar wave equation with complex velocity	365
		11.4.1 Spatial Q	366
	11.5	Attenuation of seismic waves in the Earth	367
	11.6	Mathematical aspects of causality and applications	370
		11.6.1 The Hilbert transform. Dispersion relations	371

xii	Contents	
	11.6.2 Minimum-phase-shift functions	372
	11.6.3 The Paley–Wiener theorem. Applications	375
11.7	Futterman's relations	377
11.8	Kalinin and Azimi's relation. The complex wave velocity	381
11.9	t^*	384
11.10) The spectral ratio method. Window bias	384
11.11	Finely layered media and scattering attenuation	386
Hints	3	391
Appe	ndices	407
А	Introduction to the theory of distributions	407
В	The Hilbert transform	419
С	Green's function for the 3-D scalar wave equation	422
D	Proof of (9.5.12)	425
Е	Proof of (9.13.1)	428
Bibli	ography	431
Index	c	439

Preface

The study of the theory of elastic wave propagation and generation can be a daunting task because of its inherent mathematical complexity. The books on the subject currently available are either advanced or introductory. The advanced ones require a mathematical background and/or maturity generally beyond that of the average seismology student. The introductory ones, on the other hand, address advanced subjects but usually skip the more difficult mathematical derivations, with frequent references to the advanced books. What is needed is a text that goes through the complete derivations, so that readers have the opportunity to acquire the tools and training that will allow them to pose and solve problems at an intermediate level of difficulty and to approach the more advanced problems discussed in the literature. Of course, there is nothing new in this idea; there are hundreds of physics, mathematics, and engineering books that do just that, but unfortunately this does not apply to seismology. Consequently, the student in a seismology program without a strong quantitative or theoretical component, or the observational seismologist interested in a clear understanding of the analysis or processing techniques used, do not have an accessible treatment of the theory. A result of this situation is an ever widening gap between those who understand seismological theory and those who do not. At a time when more and more analysis and processing computer packages are available, it is important that their users have the knowledge required to use those packages as something more than black boxes.

This book was designed to fill the existing gap in the seismological literature. The guiding philosophy is to start with first principles and to move progressively to more advanced topics without recourse to "it can be proved" or references to Aki and Richards (1980). To fully benefit from the book the reader is expected to have had exposure to vector calculus and partial differential equations at an introductory level. Some knowledge of Fourier transforms is convenient, but except for a section in Chapter 6 and Chapter 11 they are little used. However, it is also expected

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xiv

Preface

that readers without this background will also profit from the book because of its explanatory material and examples.

The presentation of the material has been strongly influenced by the books of Ben-Menahem and Singh (1981) and Aki and Richards (1980), but has also benefited from those of Achenbach (1973), Burridge (1976), Eringen and Suhubi (1975), Hudson (1980), and Sokolnikoff (1956), among others. In fact, the selection of the sources for the different chapters and sections of the book was based on a "pick and choose" approach, with the overall goal of giving a presentation that is as simple as possible while at the same time retaining the inherent level of complexity of the individual topics. Again, this idea is not new, and is summarized in the following statement due to Einstein, "everything should be made as simple as possible, but not simpler" (quoted in Ben-Menahem and Singh's book). Because of its emphasis on fundamentals, the book does not deal with observations or with data analysis. However, the selection of topics was guided in part by the premise that they should be applicable to the analysis of observations. Brief chapter descriptions follow.

The first chapter is a self-contained introduction to Cartesian tensors. Tensors are essential for a thorough understanding of stress and strain. Of course, it is possible to introduce these two subjects without getting into the details of tensor analysis, but this approach does not have the conceptual clarity that tensors provide. In addition, the material developed in this chapter has direct application to the seismic moment tensor, discussed in Chapters 9 and 10. For completeness, a summary of results pertaining to vectors, assumed to be known, is included. This chapter also includes an introduction to dyadics, which in some cases constitute a convenient alternative to tensors and are found in some of the relevant literature.

Chapters 2 and 3 describe the strain and rotation tensors and the stress tensor, respectively. The presentation of the material is based on a continuum mechanics approach, which provides a conceptually clearer picture than other approaches and has wide applicability. For example, although the distinction between Lagrangian and Eulerian descriptions of motion is rarely made in seismology, the reader should be aware of them because they may be important in theoretical studies, as the book by Dahlen and Tromp (1998) demonstrates. Because of its importance in earth-quake faulting studies, the Mohr circles for stress are discussed in detail. Chapter 4 introduces Hooke's law, which relates stress and strain, and certain energy relations that actually permit proving Hooke's law. The chapter also discusses several classic elastic parameters, and derives the elastic wave equation and introduces the P and S waves.

Chapter 5 deals with solutions to the scalar and vector wave equations and to the elastic wave equation in unbounded media. The treatment of the scalar equation is fairly conventional, but that of the vector equations is not. The basic idea in solving

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Preface

them is to find vector solutions, which in the case of the elastic wave equation immediately lead to the concept of P, SV, and SH wave motion. This approach, used by Ben-Menahem and Singh, bypasses the more conventional approach based on potentials. Because displacements, not potentials, are the observables, it makes sense to develop a theory based on them, particularly when no additional complexity is involved.

The P, SV, and SH vector solutions derived in Chapter 5 are used in Chapter 6, which covers body waves in simple models (half-spaces and a layer over a half-space). Because of their importance in applications, the different cases are discussed in detail. Two important problems, generally ignored in introductory books, also receive full attention. One is the change in waveform shapes that takes place for angles of incidence larger than the critical. The second problem is the amplification of ground motion caused by the presence of a surficial low-velocity layer, which is of importance in seismic risk studies.

Chapter 7 treats surface waves in simple models, including a model with continuous vertical variations in elastic properties, and presents a thorough analysis of dispersion. Unlike the customary discussion of dispersion in seismology books, which is limited to showing the existence of phase and group velocities, here I provide an example of a dispersive system that actually shows how the period of a wave changes as a function of time and position.

Chapter 8 deals with ray theory for the scalar wave equation and the elastic wave equation. In addition to a discussion of the kinematic aspects of the theory, including a proof of Fermat's principle, this chapter treats the very important problem of P and S amplitudes. This is done in the so-called ray-centered coordinate system, for which there are not readily available derivations. This coordinate system simplifies the computation of amplitudes and constitutes the basis of current advanced techniques for the computation of synthetic seismograms using ray theory.

Chapter 9 begins the discussion of seismic point sources in unbounded media. The simplest source is a force along one of the coordinate axes, but obtaining the corresponding solution requires considerable effort. Once this problem has been solved it is easy to find solutions to problems involving combinations of forces such as couples and combinations thereof, which in turn lead to the concept of the moment tensor. Chapter 10 specializes to the case of earthquakes caused by slip on a fault, which is shown to be equivalent to a double couple. After this major result it is more or less straightforward to find the moment tensor corresponding to a fault of arbitrary orientation. Although the Earth is clearly bounded and not homogeneous, the theory developed in these two chapters has had a major impact in seismology and still constitutes a major tool in the study of earthquakes, particularly in combination with ray theory.

xv

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xvi

Preface

Chapter 11 is on attenuation, a subject that is so vast and touches on so many aspects of seismology and physics that actually it deserves a book devoted exclusively to it. For this reason I restricted my coverage to just the most essential facts. One of these is the constraint imposed by causality, which plays a critical role in attenuation studies, and because it is not well covered in most seismology books it has been given prominence here. Causality has been studied by mathematicians, physicists and engineers, and a number of basic theorems rely on the theory of complex variables. Consequently, some of the basic results had to be quoted without even attempting to give a justification, but aside from that the treatment is self-contained. The measurement of attenuation using seismic data has received a large amount of attention in the literature, and for this reason it is not discussed here except for a brief description of the widely used spectral ratio method, and a little-known bias effect introduced when the method is applied to windowed data. As scattering may be a strong contributor to attenuation, this chapter closes with an example based on the effect of a finely layered medium on wave amplitudes and shapes.

The book ends with several appendices designed to provide background material. Appendix A introduces the theory of distributions, which is an essential tool in the study of partial differential equations (among other things). Dirac's delta is the best known example of a distribution, and is customarily introduced as something that is not a "normal" function but then is treated as such. This lack of consistency is unnecessary, as the most basic aspects of distribution theory are easy to grasp when presented with enough detail, as is done in this Appendix. Distributions are already part of the geophysical and seismological literature (e.g., Bourbié et al., 1987; Dahlen and Tromp, 1998), and this Appendix will allow the reader to gain a basic understanding of the concepts discussed there. Appendix B discusses the Hilbert transform, which is a basic element in studies involving causality, and is needed to describe waves incident on a boundary at angles larger than the critical angle. A recipe for the numerical computation of the transform is also given. Appendix C derives the Green's function for the 3-D scalar wave equation. This Green's function is essential to solving the problems discussed in Chapter 9, but in spite of its importance it is usually quoted, rather than derived. The last two appendices derive in detail two fundamental equations given in Chapter 9 for the displacements caused by a single force and by an arbitrary moment tensor.

The book includes some brief historical notes. More often than not, scientific books present a finished product, without giving the readers a sense of the struggle that generally preceded the formalization of a theory. Being aware of this struggle should be part of the education of every future scientist because science rarely progresses in the neat and linear way it is usually presented. Seismology, as well as elasticity, upon which seismology is founded, also had their share of controversy,

Preface

and it is instructive to learn how our present understanding of seismic theory has come about. In this context, an enlightening review of the history of seismology by Ben-Menahem (1995) is highly recommended.

An important component of the book are the problems. Going through them will help the reader solidify the concepts and techniques discussed in the text. All the problems have hints, so that solving them should not be difficult after the background material has been mastered. In addition, full solutions are provided on a dedicated website:

http://publishing.cambridge.org/resources/0521817307

Because of the obvious importance of computers in research and because going from the theory to a computer application is not always straightforward, Fortran and Matlab codes used to generate most of the figures in Chapters 6–10 have been provided on the same website.

The book is based on class notes developed for a graduate course I taught at the University of Memphis over more than ten years. The amount of material covered depended on the background of the students, but about 70% was always covered.

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