Second Edition

Fundamentals of EARTHQUAKE ENGINEERING

From Source to Fragility

Amr S. Elnashai • Luigi Di Sarno

with website

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FROM SOURCE TO FRAGILITY

Second Edition

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Preface

This book forms one part of a complete system for university teaching and learning the fundamentals of earthquake engineering at the graduate level. The other components are the slides sets, the solved examples, including the comprehensive project, and a free copy of the computer program Zeus-NL, which are available on the book web site. The book is cast in a framework with three key components, namely (i) earthquake causes and effects are traced from source to society, (ii) structural response under earthquake motion is characterised primarily by the varying and interrelated values of stiffness, strength and ductility and (iii) all structural response characteristics are presented on the material, section, member, sub-assemblage and structural system levels. The first four chapters of the book cover an overview of earthquake causes and effects, structural response characteristics, features and representations of strong ground motion and modelling and analysis of structural systems, including design and assessment response quantities. The fifth and sixth chapters are a feature of the second edition whereby two important and advanced topics that have reached a degree of maturity are addressed. Chapter 5 presents probabilistic fragility analysis required in assessing earthquake impact on populations of structures. Chapter 6 deals with the important topic of soil–structure interaction which affects all measures of response analysis and vulnerability to earthquakes. The slides sets cover Chapters 1–6, and follow closely the contents of the book, while being a succinct summary of the main issues addressed in the text necessary for a graduate course. The slides set are intended for use by professors in the lecture room, and should be made available to the students only at the end of each chapter. They are designed to be also a capping revision tool for students. The solved examples are comprehensive and address all the important and intricate sub-topics treated in this book. The comprehensive project is used to provide an integration framework for the various components of the earthquake source, path, site and structural features that affect the actions and deformations required for seismic design. The three teaching and learning components of (i) the book, (ii) the slides sets and (iii) the solved examples are inseparable. Their use in unison has been tested and proven in a US top tier university teaching environment for a number of years.

Foreword

Congratulations to both authors! A new approach for instruction in Earthquake Engineering has been developed. This package provides a new and powerful technique for teaching – it incorporates a book, worked problems and comprehensive instructional slides available on the web site. It has undergone numerous prior trials at the graduate level as the text was being refined.

The book, in impeccable English, along with the virtual material, is something to behold. 'Intense' is my short description of this book and accompanying material, crafted for careful study by the student, so much so that the instructor is going to have to be reasonably up - to - date in the field in order to use it comfortably. The writer would have loved to have had a book like this when he was teaching Earthquake Engineering.

In this second edition, the text has six main chapters and two appendices. The six main chapters centre on (a) Earthquake Characteristics, (b) Response of Structures, (c) Earthquake Input Motion, (d) Response Evaluation, (e) Fragility Relationships for Structures and (f) Seismic Soil–Structure Interaction, with two valuable appendices dealing with Structural Configurations and Systems for Effective Earthquake Resistance, and Damage to Structures. The presentation, based on stiffness, strength and ductility concepts, comprises a new and powerful way of visualizing many aspects of the inelastic behaviour that occurs in structures subjected to earthquake excitation.

The book is written so as to be appropriate for international use and sale. The text is supplemented by numerous references, enabling the instructor to pick and choose sections of interest, and to point thereafter to sources of additional information. It is not burdened by massive reference to current codes and standards in the world. Unlike most other texts in the field, after studying this book, the students should be in a position to enter practice and adapt their newly acquired education to the use of regional seismic codes and guidelines with ease, as well as topics not covered in codes. Equally importantly, students who study this book will understand the bases for the design provisions.

Finally, this work has application not only in instruction, but also in research. Again, the authors are to be congratulated on developing a valuable work of broad usefulness in the field of earthquake engineering.

William J. Hall
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Acknowledgements

We have written this book whilst attending to our day jobs, and expanded this Second Edition while expanding our professional responsibilities along several axes. We have not taken a summer off, or went on sabbatical leave. It has therefore been difficult to extract ourselves from the immediate and more pressing priorities of ongoing academic and personal responsibilities. That authoring the book took four years, and revising it and adding the two chapters took over a year is somewhat frustrating. The extended period has however resulted in an improved text through the feedback of end-users, mainly graduate students of exceptional talent at the University of Illinois. With the inclusion of Professor Oh-Sung Kwon from the University of Toronto (author of Chapter 6 on soil-structure interaction), we included feedback from his students concerning the same chapter. Our first thanks therefore go to our students who endured the experimental material they were subjected to and who provided absolutely essential feedback. We are also grateful to a number of world-class researchers and teachers who voluntarily reviewed the book and provided some heart-warming praise alongside some scathing criticism. These are, in alphabetical order, in memoriam of Nicholas Ambraseys, Emeritus Professor at Imperial College; Mihail Garevski, Professor and Director, Institute of Seismology and Earthquake Engineering, University of Skopje ‘Kiril and Methodius’; Ahmed Ghobarah, Professor at McMaster University; William Hall, Emeritus Professor at the University of Illinois; and Sashi Kunnath, Professor at the University of California. Special thanks are due to Professor Gordon Warn, at the Civil and Environmental Engineering Department, the Pennsylvania State University, for his meticulous revision of Chapter 5 on fragility analysis. Many other colleagues have read parts of chapters and commented on various aspects of the book, the set of slides and the worked examples. Finally our thanks go to six anonymous reviewers who were contacted by Wiley Intersciences to assess the book proposal, and to all Wiley staff who have been invariably supportive and patient over the years.

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Introduction

I.1 Context, Framework and Scope

Earthquakes are one of the most devastating natural hazards that cause great loss of life and livelihood. On average, 10 000 people die each year due to earthquakes, while annual economic losses are in the billions of dollars and often constitute a large percentage of the gross national product (GNP) of the country affected.

Over the past few decades earthquake engineering has developed as a branch of engineering concerned with the estimation of earthquake consequences and the mitigation of these consequences. It has become an interdisciplinary subject involving seismologists, structural and geotechnical engineers, architects, urban planners, information technologists and social scientists. This interdisciplinary feature renders the subject both exciting and complex, requiring its practitioners to keep abreast of a wide range of rapidly evolving disciplines. In the past few years, the earthquake engineering community has been reassessing its procedures, in the wake of devastating earthquakes which caused extensive damage, loss of life and property (e.g. Northridge, California, 17 January 1994; $30 billion and 60 dead; Hyogo-ken Nanbu, Japan, 17 January 1995; $150 billion and 6000 dead).

The aim of this book is to serve as an introduction to and an overview of the latest structural earthquake engineering. The book deals with aspects of geology, engineering seismology and geotechnical engineering that are of service to the earthquake structural engineering educator, practitioner and researcher. It frames earthquake structural engineering within a framework of balance between ‘Demand’ and ‘Supply’ (requirements imposed on the system versus its available capacity for action and deformation resistance).

In a system-integrated framework, referred to as ‘From Source-to-Society’, where ‘Source’ describes the focal mechanisms of earthquakes, and ‘Society’ describes the compendium of effects on complex societal systems, this book presents information pertinent to the evaluation of actions and deformations imposed by earthquakes on structural systems. It is therefore a ‘Source-to-Structure’ text. Source parameters, path and site characteristics are presented at a level of detail sufficient for the structural earthquake engineer to understand the effect of geophysical and seismological features on strong ground-motion characteristics pertinent to the evaluation of the response of structures. Structural response characteristics are reviewed and presented in a new framework of three quantities: stiffness, strength and ductility, which map onto the three most important limit states of serviceability, structural damage control and collapse prevention. This three-parameter approach also matches well with the consequential objectives of reducing downtime, controlling repair costs and protecting life. By virtue of the fact that the text places strong emphasis on the varying values of stiffness, strength and ductility as a function of the available deformation capacity, it blends seamlessly with deformation-based design concepts and multi-limit state design, recently referred to as performance-based design. The book stops where design codes start, at the stage of full and detailed evaluation of elastic and inelastic actions and deformations to which structures are likely to be subjected. Emphasis is placed on buildings and bridges, and material treatment is constrained to steel and concrete. The scope of the book is depicted in Figure I.1.

Chapter 1 belongs to the Demand sub-topic and is a standard exposé of the geological, seismological and earth sciences aspects pertinent to structural earthquake engineering. It concludes with two sections; one on earthquake damage, bolstered by a detailed Appendix of pictures of damaged buildings and bridges categorised according to the cause of failure. The last section is on earthquake losses and includes global statistics as well as description of the various aspects of impact of earthquakes on communities in a regional context.

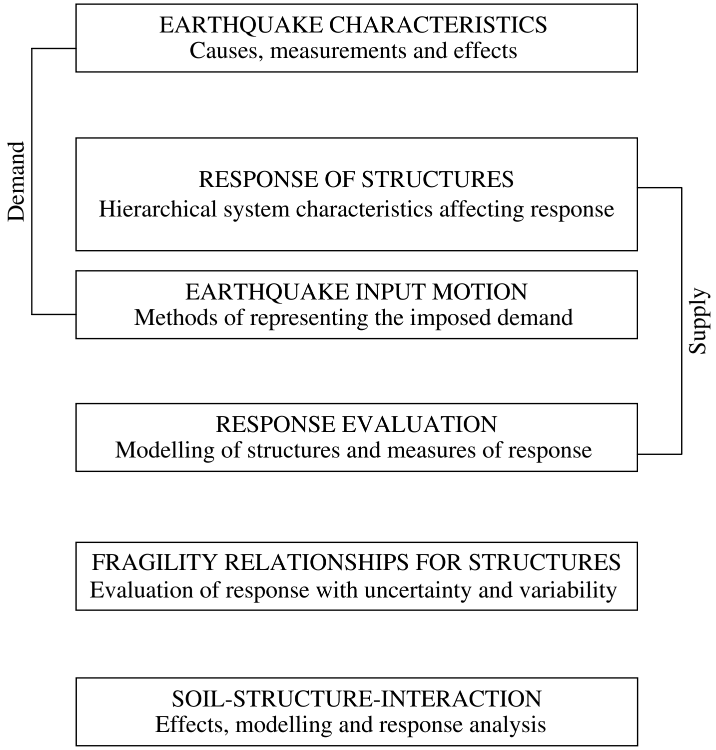

Figure I.1 Scope of the book.

Chapter 2, which belongs to the Supply or Capacity sub-topic, establishes a new framework of understanding structural response and relating milestones of such a response to (i) probability of occurrence of earthquakes and (ii) structural and societal limit states. Viewing the response of structures in the light of three fundamental parameters, namely stiffness, strength and ductility, and their implications on system performance opens the door to a new relationship between measured quantities, limit states and consequences, as described in Table 2.1. The two most important 'implications' of stiffness, strength and ductility are overstrength and damping. The latter two parameters have a significant effect on earthquake response and are therefore addressed in detail. All five response quantities of (i) stiffness, (ii) strength, (iii) ductility, (iv) overstrength and (v) damping are related to one another and presented in a strictly hierarchical framework of the five levels of the hierarchy, namely (i) material, (ii) section, (iii) member, (iv) connection and (v) system. Finally, principles of capacity design are demonstrated numerically and their use to improve structural response is emphasised.

Chapter 3 brings the readers back to description of the Demand sub-topic and delves into a detailed description of the input motion in an ascending order of complexity. It starts with point estimates of peak ground parameters, followed by simplified, detailed and inelastic spectra. Evaluation of the required response modification factors, or the demand response modification factors, is given prominence in this chapter, to contrast the capacity response modification factors addressed in Chapter 2. The chapter concludes with selection and scaling of acceleration time histories as well as a discussion of the significance of duration on response of inelastic structures.

Chapter 4 concludes the Supply sub-topic by discussing important aspects of analytically representing the structure and the significance or otherwise of some modelling details. The chapter is presented in a manner consistent with Chapter 2 in terms of dealing with modelling of materials, sections, members, connections, sub-assemblages and systems. The final section of Chapter 4 presents expected and important outcomes from analytical modelling for use in assessment of the adequacy of the structure under consideration as well as conventional design forces and displacements. The chapter also includes a brief review of methods of quasi-dynamic and dynamic analysis pertinent to earthquake response evaluation.

Chapter 5, which is a feature of the second edition, addresses the important issue of probabilistic fragility analysis, a necessary component of regional as well as structure-specific failure probability assessment. The chapter addresses required limit states, input motion characterisation and definition of the statistical model. Applications are given to support the understanding of the concepts used in the chapter to assess the probability of reaching or exceeding limit states of performance.

Chapter 6, which is also a new section of the second edition, provides an overview of the soil–structure interaction (SSI) problem and modelling methods as well as offer the perspective of a structural earthquake engineer. Due to the broad scope of the topic, this chapter does not provide a step-by-step guide on how to develop a model and run an analysis, which would require an entire book. Conversely, it includes coherent and concise descriptions of typical effects of SSI, different methods for modelling and analysing a soil-foundation and structural system. A few representative examples of SSI analyses are introduced and the findings from each case study are summarised.

I.2 Use Scenarios

I.2.1 Postgraduate Educators and Students

As discussed in the preceding section, the book was written with the university professor in mind as one of the main users alongside students attending a graduate course. It therefore includes a large number of work assignments and additional worked examples, provided on the book web site. Most importantly, summary slides are also provided on the book web site. The slides are intended to be used in the classroom, and in final revision by students. The book and the slides have been used in teaching the postgraduate level course in earthquake engineering at the University of Illinois at Urbana-Champaign for a number of years, and are therefore successfully tested in a leading university environment. Parts of the book were also used in teaching short courses on a number of occasions in different countries. For the earthquake engineering professor, the whole book is recommended for postgraduate courses, with the exception of methods of analysis (Section 4.7) which are typically taught in structural dynamics courses that should be a prerequisite to this course. Fragility curves and soil–structure interaction (illustrated in Chapters 5 and 6, respectively) can be conveniently taught in a specialised course for earthquake risk analysis.

I.2.2 Researchers

The book is also useful to researchers who have studied earthquake engineering in a more traditional context, where strength and direct assessment for design were employed, as opposed to the integrated strength-deformation and capacity assessment for design approach presented in this book. Moreover structural earthquake engineering researchers will find Chapter 3 of particular interest because it bridges the conventional barriers between engineering seismology and earthquake engineering and brings the concepts from the former in a palatable form to the latter. From the long experience of working with structural earthquake engineers, Chapter 3 is recommended as an essential read prior to undertaking research, even for individuals who have attended traditional earthquake engineering courses. Researchers from related fields, such as geotechnical earthquake engineering or structural control, may find Chapter 2 of value, since it heightens their awareness of the fundamental requirements of earthquake response of structures and the intricate relationship between stiffness, strength, ductility, overstrength and damping.

The newly added Chapters 5 and 6 include relevant discussions that are of interest for researchers dealing with earthquake loss estimation. These chapters provide the state-of-the-art of deriving fragility relationships and illustrate the modelling and analysis procedures for accounting for the SSI phenomena.

I.2.3 Practitioners

Practising engineers with long and relatively modern experience in earthquake resistant design in high seismicity regions will find the book on the whole easy to read and rather basic. They may, however, appreciate the presentation of fundamental response parameters and may find their connection to the structural and societal limit states refreshing and insightful. They may also benefit from the modelling notes of Chapter 4, since use is made of concepts of finite element representation in a specifically earthquake engineering context. Many experienced structural earthquake engineering practitioners will find Chapter 3 on input motion useful and practical. The chapter will aid them in selection of appropriate characterisation of ground shaking. The book as a whole, especially Chapters 3 and 4 is highly recommended for practising engineers with limited or no experience in earthquake engineering. The newly added Chapter 6 provides practical guidelines for the modelling and analysis procedures accounting for the SSI in the earthquake response of systems.

List of Abbreviations

AI = Arias Intensity
AIJ = Architectural Institute of Japan
ASCII = American Standard Code for Information Interchange
ATC = Applied Technology Council
BF = Braced Frame
CBF = Concentrically Braced Frame
CEB = Comité Euro-international du Beton
CEUS = Central and Eastern United States
CONV = Convolution
COSMOS = Consortium of Organisations for Strong-Motion Observation Systems
COV = Coefficient Of Variation
CP = Collapse Prevention
CQC = Complete Quadratic Combination
CSMIP = California Strong-Motion Instrumentation Program
CSUN = California State University Northridge
CTBUH = Council on Tall Building and Urban Habitat
CUE = Conference on Usage of Earthquakes
DC = Damage Control
DI = Damage Index
DL = Dead Load
DPM = Damage Probability Matrix
EBF = Eccentrically Braced Frame
EERI = Earthquake Engineering Research Institute
ELF = Equivalent Lateral Force
EPM = Elastic-Plastic Model
EPP = Elastic Perfectly-Plastic
EMS = European Modified Scale
EQ = Earthquake
FE = Finite Element

FF = Fragility Function
FEMA = Federal Emergency Management Agency
FORM = First-Order Reliability Method
FOSM = First-Order Second Moment
FRP = Fibre-Reinforced Plastic
FW = Frame-Wall structure
GM = Ground Motion
GNP = Gross National Product
HDS = Hybrid Distributed Simulation
HF = Hybrid Frame
HPGA = Horizontal Peak Ground Acceleration
ICSMD = Imperial College Strong-Motion Databank
ID = Inter-storey Drift
IDA = Incremental Dynamic Analysis
IF = Irregular Frame
IM = Intensity Measure
JMA = Japanese Meteorological Agency
KBF = Knee-Braced Frame
K-NET = Kyoshin Net
LEM = Linear Elastic Model
LENLH = Linear Elastic-Plastic with Non-Linear Hardening
LEPP = Linear Elastic-Perfectly Plastic
LESH = Linear Elastic-Plastic with Strain Hardening
LL = Live Load
LQ = Love Wave
LR = Rayleigh Wave
LRH = Linear Response History
LS = Limit State
MCS = Mercalli-Cancani-Seiberg
MCSM = Monte Carlo Simulation Method
MDOF = Multi-Degree-Of-Freedom
MM = Modified Mercalli
MP = Menegotto-Pinto model
MRF = Moment-Resisting Frame
MSK = Medvedev-Sponheuer-Karnik
NGA = New Generation Attenuation
NLEM = Non-Linear Elastic Model
NRH = Non-Linear Response History
NSP = Non-Linear Static Pushover
OBF = Outrigger-Braced Frame
PA = Pushover Analysis
PDF = Probability Density Function
PGA = Peak Ground Acceleration
PGD = Peak Ground Displacement
PGV = Peak Ground Velocity
PEER = Pacific Earthquake Engineering Research Center

PL = Performance Level
PML = Perfectly Matched Layer
RC = Reinforced Concrete
RO = Ramberg-Osgood model
RF = Regular Frame
RSA = Response Spectrum Analysis
RSM = Response Surface Method
SCWB = Strong Column-Weak Beam
SDOF = Single-Degree-Of-Freedom
SH = Shear Horizontal
SI = Spectral Intensity
SL = Serviceability Limit
SORM = Second-Order Reliability Method
SPEAR = Seismic Performance Assessment and Rehabilitation
SPT = Standard Penetration Test
SRSS = Square Root of the Sum of Squares
SSI = Soil-Structure-Interaction
SV = Shear Vertical
SW = Structural Wall
TS = Tube System
URM = Unreinforced masonry
USA = United States of America
USEE = Utility Software for Earthquake Engineering
USSR = Union of Soviet Socialist Republics
VPGA = Vertical Peak Ground Acceleration
WCSB = Weak Column-Strong Beam.

List of Symbols

Symbols defined in the text that are used only once, and those which are clearly defined in a relevant figure or table, are in general not listed herein.

A_v = effective shear area
C_M = centre of mass
C_R = centre of rigidity
d = distance from the earthquake source
E = Young's modulus
E_0 = initial Young's modulus (at the origin)
E_t = tangent Young's modulus
f_c = concrete compression strength
f_t = concrete tensile strength
f_u = steel ultimate strength
f_y = steel yield strength
G = shear modulus
G_0 = initial shear modulus
G_b = shear modulus of the bedrock
g = acceleration of gravity
H = total height
H_{eff} = effective height
h = height
I = intensity
= moment of inertia
I_i = Modified Mercalli intensity of the ith isoseismal
I_{JMA} = intensity in the Japanese Meteorological Agency (JMA) scale
I_{max} = maximum intensity
I_{MM} = intensity in the Modified Mercalli (MM) scale
I_0 = epicentral intensity
J = torsional moment of inertia
K = stiffness

K_s = secant stiffness
K_t = tangent stiffness
K_y = lateral stiffness
K_0 = initial stiffness (at origin)
k_{eff} = effective stiffness
k_f = flexural stiffness
k_s = shear stiffness
K_θ = Rocking Stiffness
L_p plastic hinge length
L_w = wall length
M = magnitude
= bending moment
m_b = body wave magnitude
M_{eff} = effective mass
M_L = local (or Richter) magnitude
M_{JMA} = Japanese Meteorological Agency (JMA) magnitude
m_r = rotational mass
M_S = surface wave magnitude
m_t = translational mass
M_w = moment magnitude
N = axial load
q = force reduction factor
R = focal distance
= force reduction factor
r_i = radius of the equivalent area enclosed in the *i*th isoseismal
S_a = spectral acceleration
S_d = spectral displacement
SI_H = Housner's spectral intensity
SI_M = Matsumura's spectral intensity
S_v = spectral velocity
T = period of vibration
T_h = hardening period
T_R = return period
T_S = site fundamental period of vibration
$T_{S,n}$ = site period of vibration relative to the nth mode
T_y = yield period
t_r = reference time period
V_{base} = global base shear
V_e = elastic shear
V_i = storey shear
V_y = yield shear
V_d = design base shear
V_u = ultimate shear
v_{LQ} = velocity of Love waves
v_{LR} = velocity of Rayleigh waves
v_P = velocity of P-waves
v_S = velocity of S-waves

α_s = shear span ratio
β = logarithmic standard deviation
Γ_i = modal participation factor for the *i*th mode
γ_D, γ_E, γ_L = load factors
γ_I = importance factor
Δ = global lateral displacement
Δ_y = global yield lateral displacement
Δ_u = global ultimate lateral displacement
δ = lateral displacement
δ_i = storey lateral displacement
δ_{top} = top lateral displacement
δ_u = ultimate lateral displacement
δ_y = yield lateral displacement
ε = strain
ε_c = concrete strain
ε_{cu} = concrete crushing strain
ε_u = ultimate strain
ε_y = yield strain
θ = rotation
θ_p = plastic rotation
θ_u = ultimate rotation
θ_y = yield rotation
μ = ductility
μ_a = available ductility
μ_d = ductility demand
μ_Δ = global displacement ductility
μ_δ = displacement ductility
μ_ε = material ductility
μ_θ = rotation ductility
μ_χ = curvature ductility
ν = Poisson's ratio
ξ = damping
ξ_{eff} = effective damping
ξ_{eq} = equivalent damping
ρ = density
σ = normal stress
σ_y = yielding normal stress
χ = curvature
χ_u = ultimate curvature
χ_y = yield curvature
Ψ = combination coefficient
Ω_d = observed overstrength
Ω_i = inherent overstrength
ω = natural circular frequency
ω_i = circular frequency relative to the *i*th mode

1

Earthquake Characteristics

1.1 Causes of Earthquakes

1.1.1 Plate Tectonics Theory

An earthquake is manifested as ground shaking caused by the sudden release of energy in the Earth's crust. This energy may originate from different sources, such as dislocations of the crust, volcanic eruptions or even by man-made explosions or the collapse of underground cavities, such as mines or karsts. Thus, while earthquakes are defined as natural disturbances, different types of earthquake exist: fault rupture-induced, volcanic, mining-induced and large reservoir-induced. Richter (1958) has provided a list of major earth disturbances recorded by seismographs as shown in Figure 1.1. Tectonic earthquakes are of particular interest to the structural engineers, and further discussion will therefore focus on the latter type of ground disturbance.

Earthquake occurrence may be explained by the theory of large-scale tectonic processes, referred to as 'plate tectonics'. The theory of plate tectonics derives from the theory of continental drift and sea-floor spreading. Understanding the relationship between geophysics, the geology of a particular region and seismic activity began only at the end of the nineteenth century (Udias, 1999). Earthquakes are now recognised to be the symptoms of active tectonic movements (Scholz, 1990). This is confirmed by the observation that intense seismic activity occurs predominantly on known plate boundaries as shown in Figure 1.2.

Plates are large and stable rigid rock slabs with a thickness of about 100 km forming the crust or lithosphere and part of the upper mantle of the Earth. The crust is the outer rock layer with an internal complex geological structure and a non-uniform thickness of 25–60 km under continents and 4–6 km under oceans. The mantle is the portion of the Earth's interior below the crust, extending from a depth of about 30 km to about 2900 km; it consists of dense silicate rocks. The lithosphere moves differentially on the underlying asthenosphere, which

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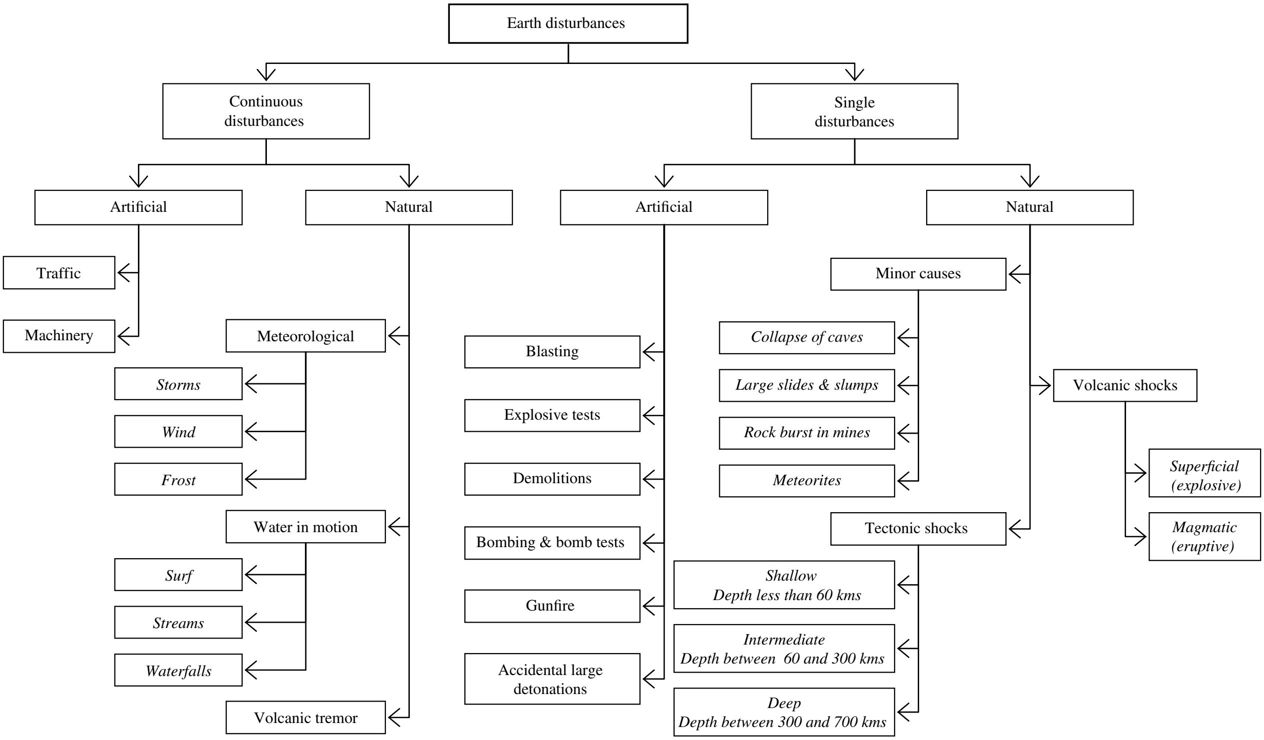

Figure 1.1 Earth disturbances recorded by seismographs.

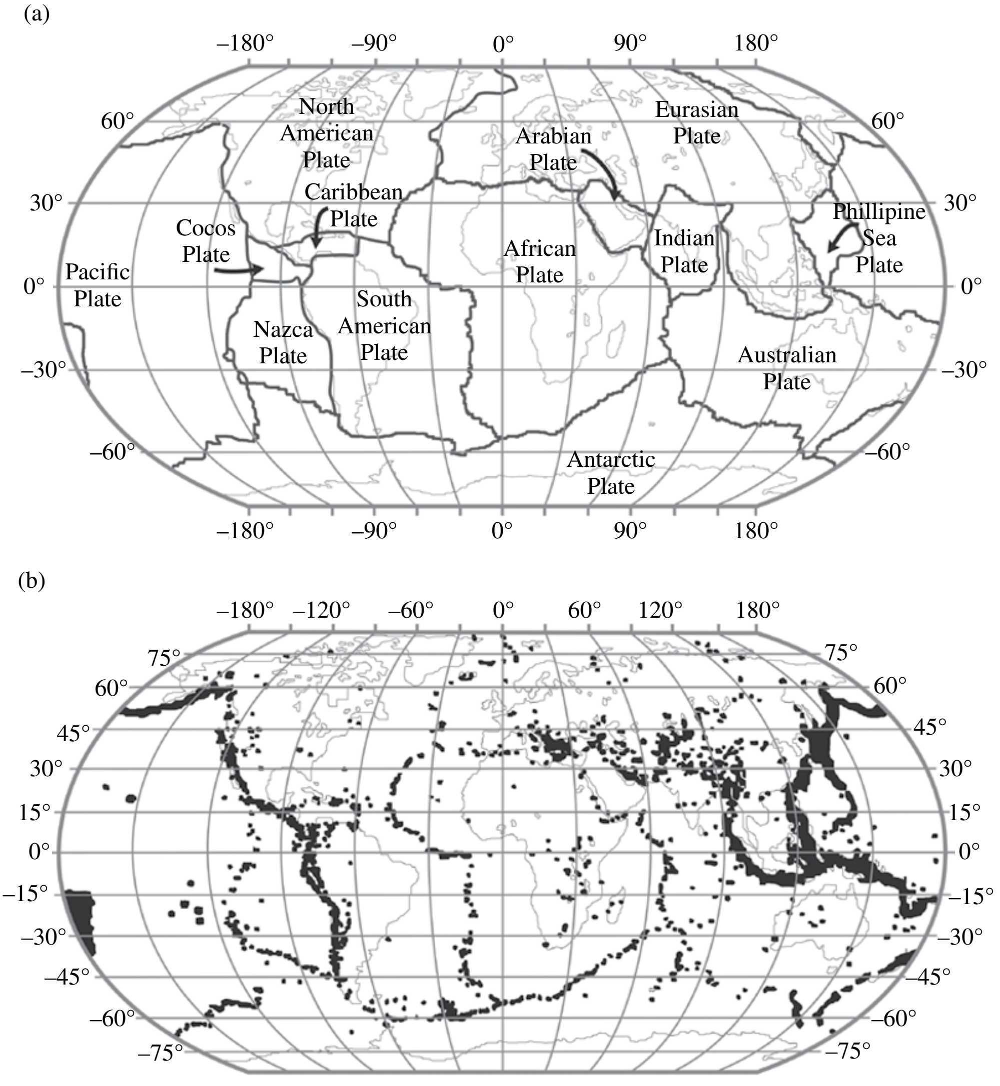

Figure 1.2 Tectonic plates (a) and worldwide earthquake distribution (b). (Adapted from Saint Louis University, Earthquake Center, USA.)

is a softer warmer layer around 400 km thick at a depth of about 50 km in the upper mantle. It is characterised by plastic or viscous flow. The horizontal movement of the lithosphere is caused by convection currents in the mantle; the velocity of the movement is about 1–10 cm/year. Current plate movement can be tracked directly by means of reliable space-based geodetic measurements, such as very long baseline interferometry, satellite laser ranging and global positioning systems.

Large tectonic forces take place at the plate edges due to the relative movement of the lithosphere–asthenosphere complex. These forces instigate physical and chemical changes and affect the geology of the adjoining plates. However, only the lithosphere has the strength and the brittle behaviour to fracture, thus causing an earthquake.

According to the theory of continental drift, the lithosphere is divided into 15 rigid plates, including continental and oceanic crusts. The plate boundaries, where earthquakes frequently occur, are also called 'seismic belts' (Kanai, 1983). The Circum-Pacific and Eurasian (or Alpine) belts are the most seismically active. The former connects New Zealand, New Guinea, the Philippines, Japan, the Aleutians, the west coast of North America and the west coast of South America. The 1994 Northridge (California) and the 1995 Kobe (Japan) earthquakes occurred along the Circum-Pacific belt. The Eurasian belt links the northern part of the Mediterranean Sea, Central Asia, the southern part of the Himalayas and Indonesia. The Indian Ocean earthquake of 26 December 2004 and the Kashmir earthquake of 8 October 2005 were generated by the active Eurasian belt.

The principal types of plate boundaries can be grouped as follows (Figure 1.3):

(i) *Divergent or rift zones:* plates separate themselves from one another and either an effusion of magma occurs or the lithosphere diverges from the interior of the Earth. Rifts are distinct from mid-ocean ridges, where new oceanic crust and lithosphere is created by sea-floor spreading. Conversely, in rifts no crust or lithosphere is produced. If rifting continues, eventually a mid-ocean ridge may form, marking a divergent boundary between two tectonic plates. The Mid-Atlantic ridge is an example of a divergent plate boundary. An example of rift can be found in the middle of the Gulf of Corinth, in Greece. However, the Earth's surface area does not change with time and hence the creation of new lithosphere is balanced by the destruction at another location of an equivalent amount of rock crust, as described below.

(ii) *Convergent or subduction zones:* adjacent plates converge and collide. A subduction process carries the slab-like plate, known as the 'under-thrusting plate', into a dipping zone, also referred to as the 'Wadati–Benioff zone', as far downward as 650–700 km into the Earth's interior. Two types of convergent zones exist: oceanic and continental

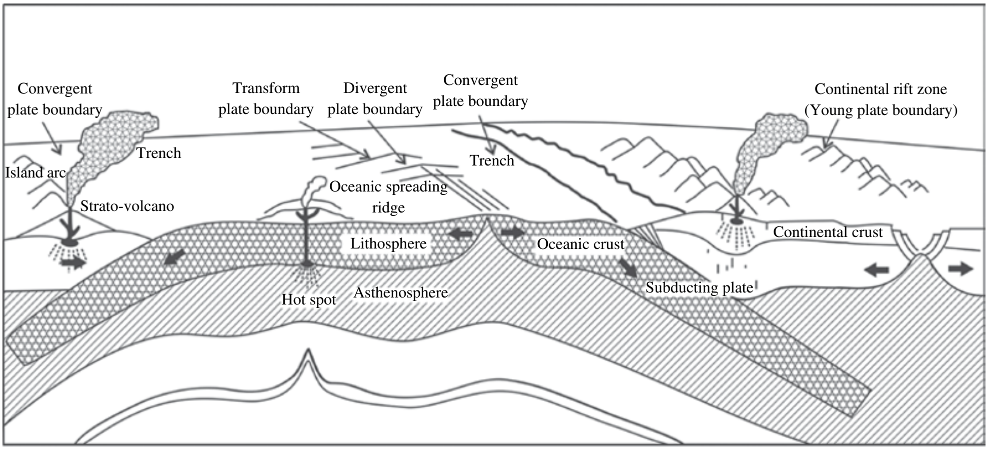

Figure 1.3 Cross-section of the Earth with the main type plate boundaries. (Adapted from USGS.)