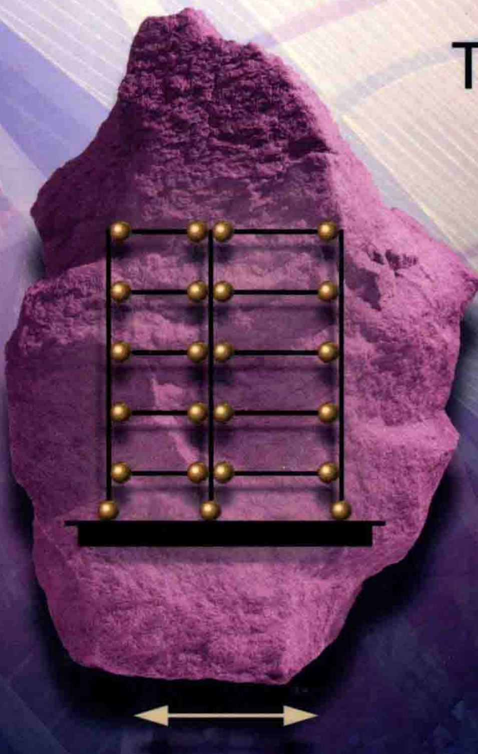
T. K. Datta



SEISMIC ANALYSIS OF STRUCTURES

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T. K. Datta
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Preface

For structural engineers, earthquake engineering can be broadly divided into three areas, namely, seismology (including ground effects), seismic analysis, and seismic design. These areas are big subjects in themselves and deserve separate treatment in exclusive books. While there are many excellent books that cover these three areas in varying proportions, none have been written exclusively on the seismic analysis of structures for use in teaching an undergraduate elective or a postgraduate core course. Furthermore, there are virtually no books that contain all aspects of the seismic analysis of structures, combining new concepts with existing ones, which graduate students pursuing research in the area of earthquake engineering would appreciate. Considering these major requirements, the present book has been written despite the fact that a number of masterly textbooks on structural dynamics and earthquake engineering, dynamics of soil structure interaction, and geotechnical earthquake engineering are already available within the earthquake engineering community, and where many of the theoretical concepts presented here have been covered more elaborately. The present book attempts to provide textbook material for the learning and teaching of the seismic analysis of structures in totality. It offers a comprehensive and unique treatment of all aspects of the seismic analysis of structures, starting with seismology and through to the seismic control of structures. The materials in the book are arranged and presented in a manner that is expected to be equally useful to both undergraduate and postgraduate students, researchers, and practicing engineers. Depending on the particular requirements, it is possible to structure courses at various levels on different aspects of seismic analysis based on the contents of this book. It is presumed that the readers have some background of structural dynamics, preferably having undergone a basic course in structural dynamics.

The book is presented in nine chapters. The first chapter, *Seismology*, deals with the fundamentals of seismology that a structural engineer must know. The chapter deals with topics such as the earth and its interior, plate tectonics, causes of earthquakes, seismic waves, earthquake measurement parameters, the measurement of earthquakes, modification of earthquake waves due to the nature of the soil, and seismic hazard analysis. The last topic describes both deterministic and probabilistic seismic hazard analyses, and seismic risk at a site. The concept of microzonation based on hazard analysis is also included.

The second chapter, *Seismic Inputs for Structures*, provides an extensive coverage of the various types of seismic inputs used for different types of seismic analysis. The seismic inputs discussed include time history records and their frequency contents, power spectral density function (PSDF) of ground motion, different types of earthquake spectra, design response spectra, probabilistic response spectra, site specific spectra, and uniform hazard spectra. Generation of the time histories of synthetic ground motion from a response spectrum and the PSDF of ground motion is also briefly discussed. Finally, predictive relationships for different seismic input parameters such as peak ground acceleration (PGA), response spectra, PSDFs, modulating functions, and coherence functions are given.

The third chapter, *Response Analysis for Specified Ground Motions*, deals with different methods of analysis of single and multi-degrees of freedom systems for specified time histories of ground motion. Methods include time domain analysis, frequency domain analysis using fast Fourier transform (FFT), modal time domain, and frequency domain analyses for both single-point and multi-point excitations.

Methods of analysis are described for both second-order and state-space equations. The mode acceleration method is also presented. At the end of the chapter, steps for developing a comprehensive program using MATLAB® are outlined, which can solve single and multi-degrees of freedom systems for a specified time history of ground motion using all of the methods of analysis discussed in the chapter. In addition, use of the SIMULINK toolbox of MATLAB to solve problems is also demonstrated.

The fourth chapter, *Frequency Domain Spectral Analysis*, introduces the concept of spectral analysis of structures, treating the ground motion as a stationary random process and deals with the subject in a manner that does not require an in-depth knowledge of the theory of random vibration. Using FFT, the fundamentals of frequency domain spectral analysis are introduced, and then the required concepts of autocorrelation, cross correlation, power spectral density functions, and so on, are presented. The basic relationship between multi-point input and output PSDFs of a structural system is given using a matrix formulation. Direct and modal spectral analyses are described for single-point and multi-point excitations. Furthermore, a method for the determination of the mean peak response from a spectral analysis is outlined.

The fifth chapter, *Response Spectrum Method of Analysis*, discusses the response spectrum method of analysis for single- and multi-point excitations of multi-degrees of freedom systems. Development of the methods is presented after a brief background of the concept of equivalent lateral load. The necessary explanation for including the effect of spatial correlation for multi-point excitation is duly incorporated in the theory. Other topics discussed in this chapter include modal combination rules, the response spectrum method of analysis for none classically damped systems and secondary systems, the base shear approach, and comparison between the code provisions of a few codes in relation to the base shear and response spectrum methods of analysis.

The sixth chapter, *Inelastic Seismic Response of Structures*, covers the methods of inelastic response analysis of structures and the fundamental aspects of inelastic behavior of structural components for earthquake forces. The topics include the hysteretic behavior of materials, the incremental method of analysis of single- and multi-degrees of freedom systems accounting for the hysteretic effects, the incremental analysis procedure with bidirectional interaction, pushover analysis, ductility demand, inelastic response spectra, and ductility in multi-storey buildings.

The first part of the seventh chapter on *Seismic Soil Structure Interaction*, provides the background to seismic wave propagation through the soil medium and gives the finite element analysis of the wave propagation problem. Next, the dynamic soil–structure interaction is presented by explaining kinematic interaction, inertial interaction, and the direct and multi-step method for bounded problems. Both the finite element method and the substructure technique for solving soil–structure and soil–pile structure interaction problems are described. The topics include time domain and frequency domain analyses using direct, substructure, and modal analysis techniques for single- and multi-point excitations, analyses for soil–pile structure interaction problems, and underground structures.

The eighth chapter, *Seismic Reliability Analysis of Structures*, deals with the seismic reliability analysis of structures in which the basic concept of reliability analysis is introduced first, followed by some popularly used techniques such as the first order second moment (FOSM) method, the Hasofer–Lind method, the second-order method, and a simulation based method for solving the reliability problems. Uncertainties involved in the seismic reliability analysis of structures are then elaborated, and a number of seismic reliability analysis techniques are presented. They include reliability analysis for threshold crossing, the first passage failure of structures, risk assessment using a damage probability matrix, and approximate probabilistic risk assessment of structures.

In the final chapter on *Seismic Control of Structures*, the concepts of passive, active, and semi-active control of structures for earthquake forces are covered. The various topics discussed in the chapter include: the design of base isolators and analysis of base isolated structures (both response spectrum and non-linear time history analyses), different methods of analysis of building frames fitted with viscoelastic dampers and tuned mass dampers, active control of structures with and without an observer using the pole placement technique, quadratic linear optimal control, and instantaneous optimal control. Finally, an introduction to the semi-active control of structures using semi-active hydraulic dampers is presented.

In each chapter, a number of carefully selected example problems are solved in order to explain the various concepts presented. In addition, many of the problems are solved using MATLAB and standard software such as SAP2000 and ABAQUAS, demonstrating the use of the available software for solving different types of problems in the seismic analysis of structures.

I would like to thank many of my students who directly or indirectly helped me in gaining insight and carrying out research in the area of seismic analysis of structures. Their invaluable contributions are hidden in every page of this book. The textbooks *Dynamics of Structures* by Professor R.W. Clough and Professor J. Penzien, *Dynamics of Structures – Theory and Application to Earthquake Engineering* by Professor A.K. Chopra, *Geotechnical Earthquake Engineering* by Professor S.L. Kramer, and *Structural Dynamics for Structural Engineers* by Garry C. Hart have been valuable references in organizing the many concepts of the book and clarifying many doubts. I am extremely grateful to these authors. I wish to acknowledge my sincere thanks to Mr. Prakash Kedia and Dr. Deepak Kumar who worked untiringly preparing the manuscript of the book. I am also thankful to many of my M.Tech students who helped me solve the example problems. Finally, I thank Dr. (Mrs.) Sabita Karunes for her support and encouragement whilst preparing the book.

The author will be pleased to hear from readers who spot errors and misprints or who find ways of improving the book. All such suggestions will be gratefully acknowledged, and will be used selectively to improve future versions of the book.

Contents

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1

Seismology

1.1 Introduction

An earthquake is a sudden and transient motion of the earth's surface. According to geologists, the earth has suffered earthquakes for hundreds of millions of years, even before humans came into existence. Because of the randomness, the lack of visible causes, and their power of destructiveness, ancient civilizations believed earthquakes to be supernatural phenomena – the curse of God. In terms of the geological time scale, it is only recently (the middle of seventeenth century) that an earthquake has been viewed as a natural phenomenon driven by the processes of the earth as a planet. Thus subsequent work, especially in nineteenth century, led to tremendous progress on the instrumental side for the measurement of earthquake data. Seismological data from many earthquakes were collected and analyzed to map and understand the phenomena of earthquakes. These data were even used to resolve the earth's internal structure to a remarkable degree, which, in turn, helped towards the development of different theories to explain the causes of earthquakes. While the body of knowledge derived from the study of collected seismological data has helped in the rational design of structures to withstand earthquakes, it has also revealed the uncertain nature of future earthquakes for which such structures are to be designed. Therefore, probabilistic concepts in dealing with earthquakes and earthquake resistant designs have also emerged.

Both seismologists and earthquake engineers use the seismological data for the understanding of an earthquake and its effects, but their aims are different. Seismologists focus their attention on the global issues of earthquakes and are more concerned with the geological aspects, including the prediction of earthquakes. Earthquake engineers, on the other hand, are concerned mainly with the local effects of earthquakes, which are capable of causing significant damage to structures. They transform seismological data into a form which is more appropriate for the prediction of damage to structures or, alternatively, the safe design of structures. However, there are many topics in seismology that are of immediate engineering interest, especially in the better understanding of seismological data and its use for seismic design of structures. Those topics are briefly presented in the following sections.

1.1.1 Earth and its Interiors

During the formation of the earth, large amounts of heat were generated due to the fusion of masses. As the earth cooled down, the masses became integrated together, with the heavier ones going towards the center and the lighter ones rising up. This led to the earth consisting of distinct layers of masses. Geological investigations with seismological data revealed that earth primarily consists of four distinct layers namely:

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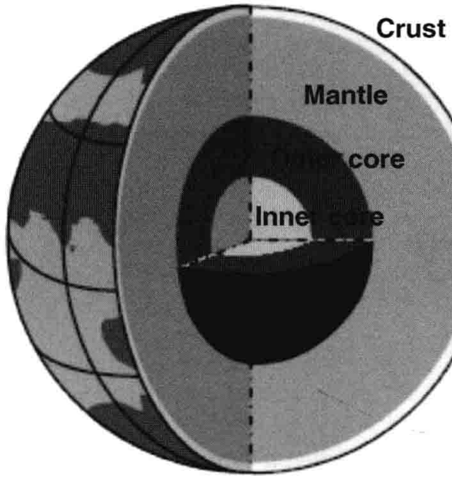

Figure 1.1 Inside the earth (*Source*: Murty, C.V.R. "IITK-BMPTC Earthquake Tips." Public domain, *National Information Centre of Earthquake Engineering*. 2005. http://nicee.org/EQTips.php - accessed April 16, 2009.)

the inner core, the outer core, the mantle, and the crust, as shown in Figure 1.1. The upper-most layer, called the crust, is of varying thickness, from 5 to 40 km. The discontinuity between the crust and the next layer, the mantle, was first discovered by Mohorovičić through observing a sharp change in the velocity of seismic waves passing from the mantle to the crust. This discontinuity is thus known as the Mohorovičić discontinuity ("M discontinuity"). The average seismic wave velocity (P wave) within the crust ranges from 4 to 8 km s^{-1}. The oceanic crust is relatively thin (5–15 km), while the crust beneath mountains is relatively thick. This observation also demonstrates the principle of isostasy, which states that the crust is floating on the mantle. Based on this principle, the mantle is considered to consist of an upper layer that is fairly rigid, as the crust is. The upper layer along with the crust, of thickness ~120 km, is known as the lithosphere. Immediately below this is a zone called the asthenosphere, which extends for another 200 km. This zone is thought to be of molten rock and is highly plastic in character. The asthenosphere is only a small fraction of the total thickness of the mantle (~2900 km), but because of its plastic character it supports the lithosphere floating above it. Towards the bottom of the mantle (1000–2900 km), the variation of the seismic wave velocity is much less, indicating that the mass there is nearly homogeneous. The floating lithosphere does not move as a single unit but as a cluster of a number of plates of various sizes. The movement in the various plates is different both in magnitude and direction. This differential movement of the plates provides the basis of the foundation of the theory of tectonic earthquake.

Below the mantle is the central core. Wichert [1] first suggested the presence of the central core. Later, Oldham [2] confirmed it by seismological evidence. It was observed that only P waves pass through the central core, while both P and S waves can pass through the mantle. The inner core is very dense and is thought to consist of metals such as nickel and iron (thickness ~1290 km). Surrounding that is a layer of similar density (thickness ~2200 km), which is thought to be a liquid as S waves cannot pass through it. At the core, the temperature is about 2500 °C, the pressure is about 4 million atm, and the density is about 14 g cm^{-3}. Near the surface, they are 25 °C, 1 atm and 1.5 g cm^{-3}, respectively.

1.1.2 Plate Tectonics

The basic concept of plate tectonics evolved from the ideas on continental drift. The existence of mid-oceanic ridges, seamounts, island areas, transform faults, and orogenic zones gave credence to the theory of continental drift. At mid-oceanic ridges, two large land masses (continents) are initially joined together. They drift apart because of the flow of hot mantle upwards to the surface of the earth at the ridges due to convective circulation of the earth's mantle, as shown in Figure 1.2. The energy of the convective flow is derived from the radioactivity inside the earth. As the material reaches the surface and cools, it forms an additional crust on the lithosphere floating on the asthenosphere. Eventually, the newly formed crust spreads outwards because of the continuous upwelling of molten rock. The new crust sinks beneath the surface of the sea as it cools down and the outwards spreading continues. These phenomena gave rise to the concept of sea-floor spreading. The spreading continues until the lithosphere reaches a deep-sea trench where it plunges downwards into the asthenosphere (subduction).

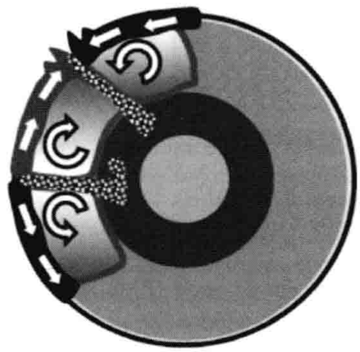

Figure 1.2 Local convective currents in the mantle (*Source*: Murty, C.V.R. "IITK-BMPTC Earthquake Tips." Public domain, *National Information Centre of Earthquake Engineering*. 2005. http://nicee.org/EQTips.php - accessed April 16, 2009.)

The continental motions are associated with a variety of circulation patterns. As a result, the continental motion does not take place as one unit, rather it occurs through the sliding of the lithosphere in pieces, called tectonic plates. There are seven such major tectonic plates, as shown in Figure 1.3, and many smaller ones. They move in different directions and at different speeds. The tectonic plates pass each other

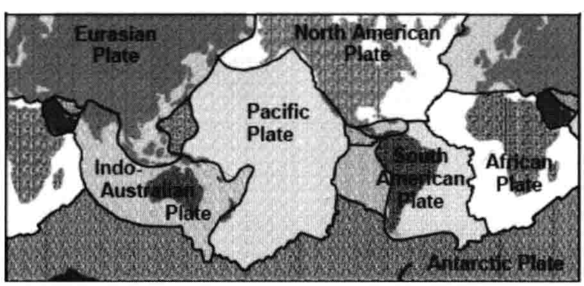

Figure 1.3 Major tectonic plates on the earth's surface (*Source*: Murty, C.V.R. "IITK-BMPTC Earthquake Tips." Public domain, *National Information Centre of Earthquake Engineering*. 2005. http://nicee.org/EQTips.php - accessed April 16, 2009.)

at the transform faults and are absorbed back into the mantle at orogenic zones. In general, there are three types of interplate interactions giving rise to three types of boundaries, namely: convergent, divergent, and transform boundaries. Convergent boundaries exist in orogenic zones, while divergent boundaries exist where a rift between the plates is created, as shown in Figure 1.4.

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