Principles of Seismology

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1 SEISMOLOGY, THE SCIENCE OF EARTHQUAKES

1.1 The historical development

The term seismology is derived from two Greek words, *seismos*, shaking, and *logos*, science or treatise. Earthquakes were called *seismos tes ges* in Greek, literally shaking of the Earth; the Latin term is *terrae motus*, and from the equivalents of these two terms come the words used in occidental languages. Seismology means, then, the science of the shaking of the Earth or the science of earthquakes. The term seismology and similar ones in other occidental languages (séismologie, sismología, sismologia, Seismologie, etc.) started to be used around the middle of the nineteenth century. Information about the main historical developments of seismology can be found in each chapter; a very short overview is given in the following paragraphs.

In antiquity, the first rational explanations of earthquakes, beyond mythical stories, are from Greek natural philosophers. Aristotle (in the fourth century BC) discussed the nature and origin of earthquakes in the second book of his treatise on meteors (*Meteorologicorum libri IV*). The term meteors was used by the ancient Greeks for a variety of phenomena believed to take place somewhere above the Earth's surface, such as rain, wind, thunder, lightning, comets, and also earthquakes and volcanic eruptions. The term meteorology derives from this word, but in modern use it refers only to atmospheric phenomena. Aristotle, following other Greek authors, such as Anaxagoras, Empedocles, and Democritus, proposed that the cause of earthquakes consists in the shaking of the Earth due to dry heated vapors underground or winds trapped in its interior and trying to leave toward the exterior. This explanation was part of his general theory for all meteors caused by various exhalations of gas or vapor (*anathymiaseis)* that extend from inside the Earth to the Lunar sphere. This theory was spread more widely by the encyclopedic Roman authors Seneca and Plinius. It was commented upon by medieval philosophers such as Albert the Great and Thomas of Aquinus, and, with small changes, was accepted in the West until the seventeenth century. For example, in 1678 A. Kircher related earthquakes and volcanoes to a system of fire conduits (*pyrophylacii)* inside the Earth. In the eighteenth century, M. Lister and N. Lesmery proposed that earthquakes are caused by explosions of flammable material concentrated in some interior regions. This explanation was accepted by Newton and Buffon.

The great Lisbon earthquake of 1 November 1755, which caused widespread destruction in that city and produced a large tsunami, may be considered the starting point of modern seismology. In 1760 J. Mitchell was the first to relate the shaking due to earthquakes to the propagation of elastic waves inside the Earth. This idea was further developed by, among others, T. Young, R. Mallet, and J. Milne. Descriptions of damage due to earthquakes and the compilation of lists of their occurrence can be traced back to very early dates. Sometimes these lists include other natural disasters such as floods, famines, and plagues. Among the first catalogs of earthquakes published in Europe are those of J. Zahn in 1696 and J. J. Moreira de Mendonça in 1758. Modern catalogs started to be published around 1850 by A. Perrey and R. Mallet (Chapter 15).

Mallet's study of the earthquake of Naples of 1857 constitutes one of the first basic works of modern seismology. Mallet developed the theory of the seismic focus from which elastic waves are propagated in all directions and connected the occurrence of earthquakes with changes in the Earth's crust that are often attended by dislocations and fractures, abandoning the explosive theory. C. Lyell and E. Suess related earthquakes to volcanic and tectonic motions, and, at the beginning of this century, F. Montessus de Ballore and A. Sieberg assigned the cause of earthquakes to orogenic processes and contributed to many aspects of observational seismology (Chapter 15). R. D. Oldham, K. Zöppritz, and E. Wiechert published the first studies of the propagation of seismic waves, based on early work on the theory of elasticity (Chapter 2). The first models of the interior of the Earth based on seismologic observations were proposed between 1900 and 1940 by, among others, R. D. Oldham, B. Gutenberg, H. Jeffreys, K. Bullen, and J. B. Macelwane (Chapter 9). The first instruments used to observe the shaking of the ground produced by earthquakes were based on the oscillations of a pendulum and started to be used around 1830. By the end of the century, the first seismographic continuous recordings had been produced. In 1889, E. von Rebeur Paschwitz recorded in Potsdam an earthquake that took place in Tokyo; this was the first seismogram recorded at a large distance. Among the first names related to the development of seismologic instrumentation are those of J. Milne and F. Omori with the inclined pendulum, E. Wiechert with the inverted pendulum, B. B. Galitzin with the electromagnetic seismograph, and H. Benioff with that of variable magnetic reluctance (Chapter 21).

Since 1945, seismology has experienced a very rapid development. Details of this development and names associated with it can be found in the introductions to each chapter and elsewhere in this book. In this rapid evolution, two important subjects are the propagation of elastic waves in the Earth and the mechanism of the generation of earthquakes. Both include theoretical and observational aspects. In the study of the propagation of seismic waves, the Earth is approximated by models that have progressed from the early very simple models of homogeneous elastic media or media divided into layers to those with three-dimensional heterogeneity including anelasticity and anisotropy (Chapters 9 and 12–14). Models of the source of earthquakes developed from simple models of point foci to those including the complex process of fracture of crustal rocks (Chapters 18 and 19). Observations of seismic waves have improved and multiplied with the development of seismologic instrumentation from early mechanical seismographs with analog recording to the present systems with a broad-band response, electronic amplification, and digital recording (Chapter 21). These developments have contributed to an increase in knowledge about the complex processes which cause earthquakes and the properties and composition of the materials of the Earth's interior. Other aspects of seismology concerning the occurrence of earthquakes, its relation to tectonic processes, and the evaluation of seismic risk have also significantly expanded (Chapter 20).

1.2 Seismology, a multidisciplinary science

Recent trends in seismology tend to overemphasize those aspects related to the generation and propagation of seismic waves. With this emphasis, Aki and Richards (1980) define seismology as a science based on data called seismograms, which are the records of mechanical vibrations. Lay and Wallace (1995), following this point of view, define seismology as the study of the generation, propagation, and recording of elastic waves in the Earth (and other celestial bodies) and of the sources that produce them, and conclude that recordings of ground motion as a function of time, or seismograms, provide the basic data for seismologists. Lomnitz (1994) considers this approach rather narrow, because seismograms provide us with much less information about earthquakes than is needed. Moreover, this definition downplays many other aspects present in the complex phenomena of earthquakes.

In a more traditional approach, seismology is defined in a broader sense, as the science of the study of earthquakes. The analysis of seismic waves forms a very important part of seismology, but not its totality. Bolt (1978) considers the task of seismologists the study of all aspects of earthquakes, including their causes, occurrence, and properties. For Bullen (1947), it is evident that the study of earthquakes belongs to many fields of knowledge such as physics, chemistry, geology, engineering, and even philosophy. For this reason, Macelwane and Sohon (1936), Madariaga and Perrier (1991), and many other authors consider seismology a multidisciplinary science.

There is no doubt that the study of seismic waves recorded by seismographs is fundamental to seismology, for example, to the study of the mechanism causing earthquakes and the constitution of the Earth's interior. However, this does not imply that wave analysis is the only source of information about earthquakes. The seismicity of a region, for example, can not be understood correctly if solely instrumentally recorded earthquakes are considered. Owing to the long return periods for large earthquakes, the study of historical earthquakes is essential. The need to go even farther back into the past has promoted the study of other types of information from archeoseismicity and paleoseismicity. The characteristics of large earthquakes can not be fully understood without geologic field observations after their occurrence. Comparison of geodesic measurements before and after earthquakes is another important source of knowledge. All these types of data are important in helping one to interpret the nature of earthquakes and their consequences, and must be integrated with the information obtained from the analysis of seismic waves.

Two parts of seismology with a marked multidisciplinary character are the evaluation of seismic risk and work toward the prediction of earthquakes. In the first case, the interaction of seismologists with geologists and engineers is necessary in order to correctly assess earthquake hazards, expected ground motion, soil conditions, seismic zonation, and the responses of structures and buildings. In the second, many of the suggested precursory phenomena (electromagnetic signals, changes in resistivity, emissions of radon gas, and changes in geodesic measurements) are not directly related to seismic waves. Progress in the problem of earthquake prediction can not be achieved without a great multidisciplinary effort involving scientists working in many fields, such as seismologists, engineers, geologists, and physicists. Finally, we must not forget that earthquakes are natural disasters that affect human lives. Depending on the correct assessment of the seismic risk and the adequacy of the design and construction of buildings, the damage from earthquakes, especially loss of human lives, may vary greatly. The response of the population to the occurrence of an earthquake must also be taken into account, with all its serious psychological, social, and economic consequences. Seismologists can not be indifferent to all these problems.

1.3 Divisions of seismology

Seismology can be divided into three disciplines: seismology in the strict sense, seismic engineering, and seismic exploration. Seismology treats the occurrence of earthquakes and their related phenomena and is primarily based on the application of the principles of the mechanics of a continuous medium and of the theory of elasticity to them. As has already been mentioned, its two main subjects are the generation of earthquakes and the vibrations and propagation of seismic waves inside the Earth. From observations of these vibrations together with other types of data, we derive our knowledge about the nature of earthquakes, the structure of the Earth's interior, and its dynamic characteristics. The part of seismology that deals with seismologic instrumentation, called seismometry, studies the physical theory of the various types of instruments used to measure seismic motion.

Seismic or earthquake engineering is an applied science that treats how the motion produced by earthquakes affects buildings and other man-made structures. Starting from the characterization of ground displacement, velocity, and acceleration, seismic engineering proceeds to consider their effects on structures and seeks to design them to resist such motions. If earthquake-resistant structures are not to be unnecessarily expensive, a reliable evaluation of the expected ground motion at a particular site is necessary. For this task, an assessment of the seismic risk for a particular zone is needed. This assessment includes the consideration of many factors, such as the occurrence of earthquakes near a site, their source mechanism, seismic-wave attenuation and soil conditions, and the vulnerability of structures. The complete evaluation of seismic risk implies the statistical analysis of all these factors and requires the collaboration of seismologists, engineers, and geologists.

In seismic exploration, seismologic methods are applied to the search for mineral resources, especially oil deposits. These methods are based on the reflection and refraction of artificially generated seismic waves in geologic structures associated with the presence of such deposits. The methods that have proved to be the most effective are those based on vertical reflection of waves. Closely spaced distributions of wave generators and detectors together with complex processing of the digital data allow one to obtain detailed images of the upper part of the Earth's crust. The increasing demand for energy resources makes this work more and more important.

1.4 Theory and observation

Just like in all experimental sciences, theoretical and observational aspects of seismology must be considered. The first are based on the principles of the mechanics of continuous media with the assumption that the Earth is an imperfectly elastic body in which vibrations are produced by earthquakes. The study of the generation of these vibrations constitutes the theory of the source mechanism. In this theory, models of the processes occurring at the focus of earthquakes are proposed. They range from the more simple ones of instantaneous point sources to the more complex. The aim is to approximate the process of fracture along geologic faults.

Vibrations in the Earth can be treated using two approaches: wave propagation and normal modes theory. The first approach considers waves propagating inside the Earth or on its surface. The second considers the eigenvibrations or oscillations of the Earth as a whole. This approach is necessary when wave lengths are near the dimensions of the Earth. In the simplest models, the Earth behaves like a homogeneous isotropic perfectly elastic medium. For some problems the flat-Earth approximation may be sufficient, whereas others require the treatment of its sphericity. Heterogeneity in the Earth can be treated using layered models with different elastic properties for each layer or models in which these properties vary with the spatial coordinates. The assumption of a spherical radially heterogeneous medium is useful in providing a close approximation to the real Earth. Ray theory is used as a high-frequency approximation to wave propagation in heterogeneous media. Surface waves in layered media describe wave dispersion with the separation of phase and group velocities. The lack of perfect elasticity is accounted for by introducing the attenuation of vibrations and waves and by considering viscoelastic models. Isotropic models are adopted as a first approximation but further analysis needs to consider anisotropic conditions. By proceeding through these successive modifications in models of the Earth, its imperfect elasticity, heterogeneity, and anisotropy can be adequately considered.

An important part of seismologic observations consists in the recording of the ground's motion by instruments installed on its surface. Nowadays classical analog seismograms on photographic paper have largely been replaced by digital data kept on magnetic tapes or compact disks, which can be obtained directly from world data banks through the Internet. Previous to their interpretation through the use of digital computers, seismologic observations usually need careful complex numerical processing. As has already been mentioned, important seismologic data are also provided by other sources, for example, historical records of damage from pre-instrumental earthquakes, field observations of structural damage and ground deformation after earthquakes, geodesic measurements related to the occurrence of earthquakes, *in situ* stress measurements and geologic and tectonic implications. Progress in the methods of observation of all kinds of seismologic data has allowed one to apply models of increasing complexity to the problems of the generation of earthquakes and the structure of the Earth's interior.

The relation between observations and theories or models can be approached through direct and inverse problems. The direct problem refers to the determination of ground displacements from theoretical models of the generation and propagation of seismic waves. In the direct problem, theoretical models are assumed *a priori* and from them synthetic displacements are determined, which are compared with observations. If they agree, we consider the model well-suited to observations. However, in many instances, there is no assurance of its uniqueness and many other models may equally well satisfy the same observations. The inverse problem consists in the estimation of the parameters of a theoretical model from observations. This is often a more complicated problem than the direct one. Observations are always incomplete and contain errors, so that a solution of the inverse problem may exist only in a probabilistic sense. In general, inverse problems become more intractable as the number of parameters of the model increases. The mathematics of inverse problems requires, generally, the solution of nonlinear integral equations. Linearization of the problem is a standard procedure that leads, very often, to large unstable systems of equations. Difficulties in the solution of inverse problems lead to their substitution by repeated solutions of direct problems until sufficient agreement between observations and synthetic data predicted by the assumed models is reached.

1.5 International cooperation

The main objectives of seismology require the cooperation of, and exchange of observations among, scientists from different parts of the world. This collaboration was accomplished from early times through private initiatives. The global character of large earthquakes soon required the establishment of institutional cooperation at national and international levels. The first organizations were national ones such as the Seismological Society of Japan, created after the earthquake of 1880 with J. Milne as first secretary. In 1890, the Committee for the Investigation of Earthquakes was founded, also in Japan, of which F. Omori was president from 1897 to 1923. In Italy, the Italian Seismological Society (Società Sismologica Italiana) was created in 1895; L. Palmieri, T. Bertelli, and G. Mercalli were among its first members. Another national society with great influence in the history of seismology is the Seismological Society of America, which was founded in 1906 as a response to the great San Francisco earthquake, with G. Davidson as its first president. The idea of an international association of seismology was first proposed by G. Gerland, during the sixth International Congress of Geography that was held in London in 1895. In 1904, the International Association of Seismology was finally created, but it was suppressed in 1916. Since 1922, seismology has formed a section of the International Union of Geodesy and Geophysics (IUGG), created in 1919. In 1930, the IUGG was reorganized and included as one of its associations the International Association of Seismology, which finally, in 1951, received its present name of the International Association of Seismology and Physics of the Earth's Interior (IASPEI). One of its commissions is the European Seismological Commission (ESC), which was founded in 1951. There are also active seismology sections of geophysical scientific societies such as the American Geophysical Union, European Geophysical Society and European Union of Geosciences.

Exchange of seismologic data between observatories was carried out in the past through the publication of seismologic bulletins. These bulletins preserve a great wealth of information about earthquakes of the early instrumental period. One of the first publications of epicenter determinations was The Reports of the Seismological Committee of the British Association for the Advancement of Science, which started in 1911 with the determinations for the period 1899–1903. In 1922, this publication became the International Seismological Summary (ISS), its first volume being dedicated to the earthquakes of 1918. Later, in 1963, the publication was continued by the

International Seismological Centre (ISC), Newbury, UK. The Bureau Central International de Séismologie (BCIS) was created in Strasbourg in 1906 and published a bulletin with epicenter determinations from 1904 until 1975. In 1976 the Centre Séismologique Européen Méditerranéen (CSEM) was created by the ESC with the task of determining hypocenters of earthquakes of the Mediterranean region. Other agencies started also to publish epicenter determinations, such as, in North America, the Jesuit Seismological Association that was active between 1925 and 1960 and the United States Coast and Geodetic Survey (USCGS), which later was transferred to the National Earthquake Information Center (NEIC), which was dependent on the United States Geological Survey. Since 1968, its monthly publication Preliminary Determination of Epicenters has included also information on determinations of focal mechanisms for sufficiently large earthquakes. Similar information has also been published since 1977 by Harvard University. At present, there are several world centers of seismologic data including digital seismograms from broad-band stations, such as the IRIS (USA), GEOFON (Germany), and ORFEUS (Holland).

1.6 Books and journals

Among the early treatises on seismology are those of Mallet (1862), *Great Neapolitan Earthquake of 1857: The First Principles of Observational Seismology* (London); Milne (1886), *Earthquakes and Other Earth Movements* (Fig. 1.1) (New York); and Hoernes (1893), *Erdbebenkunde* (Leipzig). At the beginning of this century, several books on seismology were published, among them those by Sieberg (1904), *Handbuch der Erdbebenkunde* (Braunschweig); Hobbs (1908), *Earthquakes. An Introduction to Seismic Geology* (London); Montessus de Ballore (1911), *La sismologie moderne* (Paris); and Galitzin (1914), *Vorlesungen der Seismometrie* (Leipzig).

From 1930, textbooks about seismology that may be considered modern started to be published. Only those of general character will be mentioned (full references are given in the Bibliography): Macelwane and Sohon (1936), *Introduction to Theoretical Seismology. Part I, Geodynamics* and *Part II, Seismometry*; Byerly (1942), *Seismology*; Bullen (1947), *An Introduction to the Theory of Seismology*; Richter (1958), *Elementary Seismology*; Sawarensky and Kirnos (1960), *Elemente der Seismologie und Seismometrie*; and Bath (1973), *Introduction to Seismology*.

More recently, since 1979, several textbooks on general seismology at various levels have been published. Four excellent advanced books are by Pilant (1979), *Elastic Waves in the Earth*; Aki and Richards (1980), *Quantitative Seismology. Theory and Methods*; Ben Menahem and Singh (1981), *Seismic Waves and Sources* and Dahlen and Tromp (1998) *Theoretical Global Seismology. At an introductory level there are books by Bullen and Bolt (1985), An Introduction to the Theory of Seismology*; Bolt (1978), *Earthquakes, a Primer*; Gubbins (1990), *Seismology and Plate Tectonics*; Madariaga and Perrier (1991), *Tremblements de terre*; Lay and Wallace (1995), *Modern Global Seismology*; Doyle (1995), *Seismology*; Gershanik (1995), *Sismologia*; and Udías and Mezcua (1996), *Fundamentos de sismología*.

There are books covering only certain aspects of seismology, such as, for example, wave propagation and free oscillations, by Officer (1958), Ewing *et al.* (1957), Lapwood

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AND

OTHER EARTH MOVEMENTS

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Fig. 1.1. The title page of Milne's book on seismology.

and Usami (1981), Kennett (1983), and Babuska and Cara (1991); source mechanisms, by Kasahara (1981), Kostrov and Das (1988), and Scholz (1990); seismicity, earthquake prediction, and other topics, by Gutenberg and Richter (1954), Kisslinger and Zuzuki (1978), Kulhanek (1990), and Lomnitz (1994). There are excellent collections of review papers such as those by Dziewonski and Boschi (1980), Kanamori and Boschi (1983), and Boschi *et al.* (1996). Entries on seismologic subjects in James' (1989) *The Encyclopedia of Solid Earth Geophysics* are very good short up-to-date presentations.

The first scientific articles about seismology were published in the *Bollettino del vulcanismo italiano* founded by de Rossi in 1874 and in the *Beiträge zur Geophysik*, founded by Gerland in 1887. The first journals exclusively dedicated to seismology were the *Transactions of the Seismological Society of Japan* published from 1880 to 1892 and the *Seismological Journal of Japan* published from 1892 to 1895, both directed by Milne. In 1985 the *Bollettino della Società Sismologica Italiana* was founded by the Italian Seismologic Society and, in 1897, the *Mitteilungen der Erdbeben* was founded by the Vienna Academy of Sciences. In 1907 the publication of the *Bulletin of the Imperial Earthquake Investigation Committee* started in Japan, in 1908, the *Publications du Bureau Central de l'Association International de Sismologie* started to be published in Strasbourg, in 1911, the *Bulletin of the Seismological Society of America*, in 1926, the *Bulletin of the Earthquake Research Institute* of Tokyo University, and in 1929 *Earthquakes Notes*, that changed its name to *Seismological Research Letters* in 1987. In 1997, the publication of the *Journal of Seismology* (Kluwer, Dordrecht) started. The following journals are dedicated to the field of earthquake engineering: *Earthquake Engineering and Spectral Dynamics*, *European Earthquake Engineering*, *Soil Dynamics and Earthquake Engineering*, and *Earthquake Spectron*.

Besides the journals dedicated entirely to seismology, articles on this subject are published in geophysical journals. The list is very long so only the most representative are mentioned, in chronologic order of the first year of publication: *Geophysical Magazine* (1926), *Fizica ziemly* (1937), *Pure and Applied Geophysics* (*Geofisica pura e applicata*) (1939), *Annali di geofisica* (1948), *Journal of Geophysical Research* (1949), *Journal of Physics of the Earth* (1952), *Geophysical Journal International* (1992) (a fusion of the *Geophysical Journal of the Royal Astronomical Society* (1958), the *Zeitschrift für Geophysik* (1924) and the *Annale de géophysique* (1948)), *Reviews of Geophysics* (1963), *Tectonophysics* (1964), *Earth and Planetary Science Letters* (1966), and *Physics of the Earth and Planetary Interiors* (1967).

Actually, the amount of published material in seismology keeps on increasing considerably. Students will find it useful to consult the most important textbooks, where they will find different approaches to the topics treated in this book. Also, they should read some of the classical papers, references to which are given in the Bibliography, and look through the recent issues of seismologic journals to find out about the present topics of research.