DESIGN OF EARTHQUAKE-RESISTANT BUILDINGS

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PREFACE

This book is intended for use by undergraduate and graduate students of structural engineering as well as by practicing structural engineers who are involved in the design and construction of building structures. Parts of the book will also be of interest to architects.

Structural problems which arise from earthquake action are not restricted to the geographical regions of intense earthquake activity, such as the area around the Pacific Ocean, but in fact occur in most parts of the world. This book is intended to provide information on recent world trends in earthquake engineering and should be applicable to earthquake-resistant design for any country or region. Although the book is not oriented to the situation in any particular country, regulations in the United States are often used as examples in the detailed discussions of earthquake-resistant design. These regulations are internationally well known and are often referred to by designers in other countries. Those who wish to study design specifications applying in a particular country should consult the literature of that country.

It seems that books dealing with earthquake-resistant structures are often specialized and therefore unsuitable for use as textbooks for the inexperienced reader. An attempt has been made in the present book to provide a simple, well-balanced, broad coverage of the information needed for the design of earthquake-resistant structures.

Chapter 1 first deals with the causes of earthquakes, seismic activity around the world, and damage caused by past major earthquakes. This information is of importance to architects as well as to structural engineers. Information on ground motion and its measurement is also contained in this chapter and is essential to the structural engineer for application in design practice.

Chapter 2 treats those elements of vibration theory which are closely related to earthquake-resistant design. Earthquake forces, as distinct from wind loads, act on a structure through vibration of the ground. The structural engineer should therefore be familiar with the vibration characteristics of a structure. This chapter has been written so that a reader with an undergraduate knowledge of mathematics and mechanics should easily be able to follow the development. Attention is drawn in Sec. 2.7 to the concept of aseismic safety, which is useful in evaluating structural behavior from the viewpoint of earthquake-resistant capacity.

Chapter 3 discusses the statical behavior of various structures under simulated earthquake loading. This forms the basis for earthquake-resistant design, which is dealt with in Chapter 4. In Chapter 3, strength, deformation capacity, and hysteretic behavior of members, connections, and systems are considered. Reinforced-concrete structures, steel structures, mixed structures, masonry structures, and wood structures are dealt with in turn.

Chapter 4 deals with methods of earthquake-resistant design. Detailed descriptions are first given of two methods: the static method of design, which is applied to most normal building structures; and the dynamic method of design, which is used for large-scale or important building structures. Section 4.5 takes up design questions which relate to earthquake-resistant capacity: how to select structural materials, structural forms, and framing systems. This section is particularly recommended to architects, since the earthquake-resistant capacity of a building structure is largely determined in the initial planning stages when decisions are taken with regard to structural form, layout, and materials. Section 4.7 deals with the design of equipment, facilities, and nonstructural elements such as cladding. These items have recently become of interest because of recorded damage during earthquake action.

Chapter 5 describes design methods for foundations.

Chapter 6 deals with the evaluation of the aseismic safety of existing building structures. Methods are also described for the repair of damaged structures and for the strengthening of building structures with inadequate earthquake resistance. These are quite new topics. Their importance has only recently been fully recognized, and much research work is still required.

It is my pleasure to acknowledge my gratitude to all who have helped me in the preparation of this text. My first thanks must go to Professors R. F. Warner, H. Tajimi, and Y. Kishimoto for their editorial guidance and encouragement. A number of present and former colleagues have helped in various ways. I owe deep gratitude for assistance and advice to Professors C. Matsui, T. Fujiwara, T. Nakamura, and S. Morino and to Mr. Y. Kishima and Dr. M. Nakashima. My gratitude is also extended to students who prepared figures and to Miss K. Rokuta, who typed the manuscript.

Minoru Wakabayashi

CONTENTS

CHAPTER

1

EARTHQUAKES AND GROUND MOTION

1.1 Earthquakes

1.1.1 Causes of Earthquakes

1.1.1.1 Plate Tectonics Of the various theories which have been proposed on the causes of earthquakes, the plate tectonics theory is now considered to be the most reliable. This theory tells us that the earth is covered by several layers of hard plates which act on each other to generate earthquakes. Hard tectonic plates, the *lithosphere,* sit on a comparatively soft *asthenosphere* and move as rigid bodies (Fig. 1-1). The plates measure about 70 km in thickness under the sea and twice that thickness under land. At the plate boundaries there are *midoceanic ridges, transform faults, island arcs,* and *orogenic zones.* At the midoceanic ridges, hot mantle flows up toward the surface of the earth and cools down, forming the plate, which expands horizontally. The tectonic plates pass each other at the transform faults and are absorbed back into the mantle at the orogenic zones. Earthquakes are often generated at subduction zones (Fig. 1-2) and in regions where the plates slip one against another.

Shown in Fig. 1-3 are the location of tectonic plates, the direction of

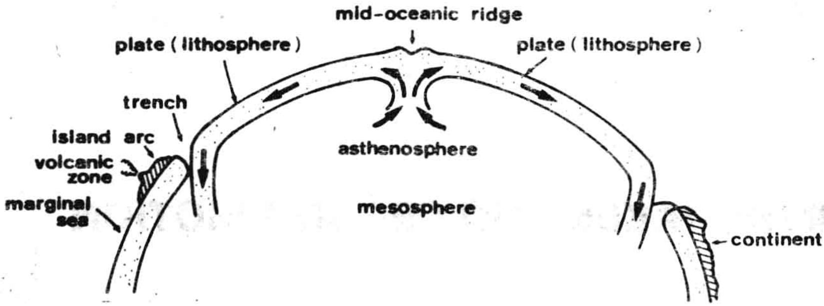


Figure 1-1 Plate tectonics.

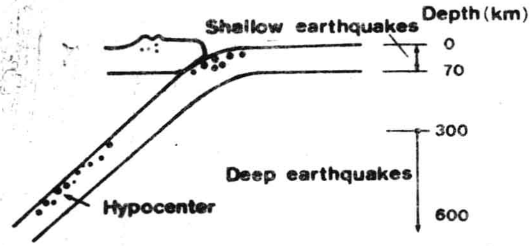


Figure 1-2 Idealized model of subduction zone and hypocenter.

plate movement, the distribution of ocean ridges, and so forth (Berlin, 1980; Bolt, 1978; Utsu, 1977). A comparison of this figure with a seismicity map (Fig. 1-11) adds credence to the plate tectonics theory.

An island arc is a chain of islands in the shape of an arc that is formed outside the marginal sea. Examples are the Kuril Islands, the Aleutian Islands, and the island chain of Japan. An island arc exhibits high seismicity potential and includes a volcano or volcanoes within its axis. Although the Pacific Ocean sides of Central and South America do not consist of islands, they are treated as island arcs since all their other characteristics are the same as those of island arcs. At the island arcs earthquakes are generated by the slip of one tectonic plate under the other. As illustrated in Fig. 1-2, these earthquakes are often deep (see Sec. 1.1.2.1).

1.1.1.2 Faults Faults are formed when mutual slip of the rock beds occurs on a certain plane. Depending upon direction, the slippages are classified as follows:

1. *Dip slip.* Slippage takes place in a vertical direction.
   a. Normal fault. The upper rock bed slips downward (Fig. 1-4*a*).
   b. Reverse fault. The upper rock bed slips upward (Fig. 1-4*b*).

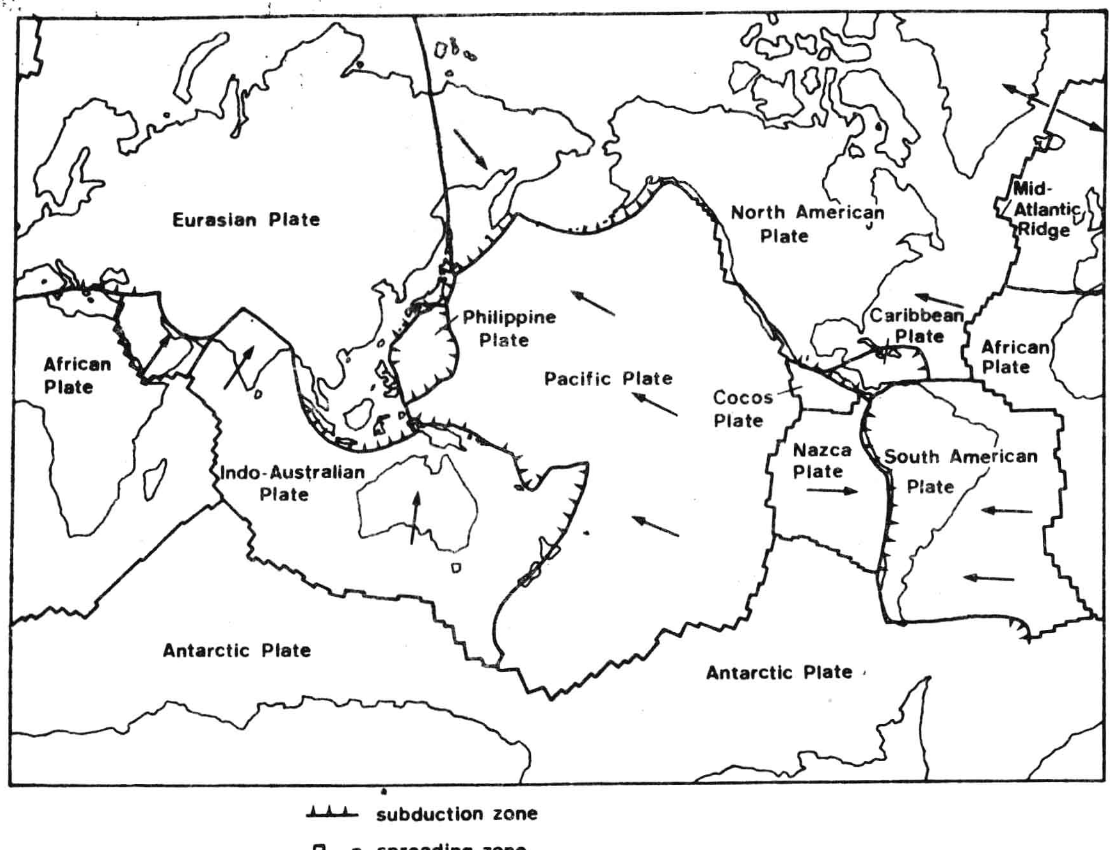
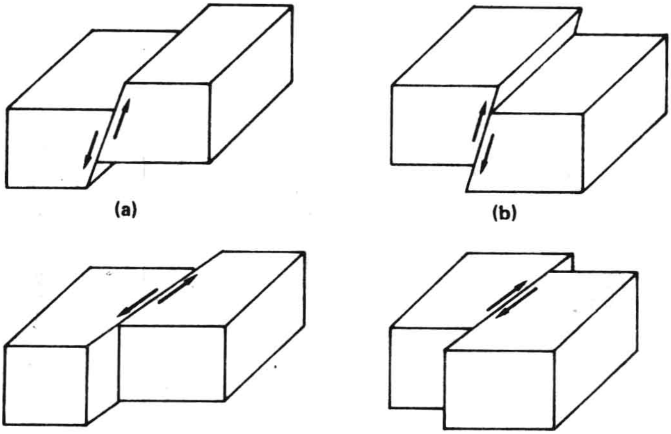


Figure 1-3 World map of tectonic plates. (*From* Earthquakes—A Primer *by B. A. Bolt. Copyright © 1978 by W. H. Freeman and Company, San Francisco. All rights reserved by B. A. Bolt.*)



(a) (b) (c) (d)

Figure 1-4 Main types of fault motion. *(a)* Normal fault. *(b)* Reverse fault. *(c)* Left lateral fault. *(d)* Right lateral fault.

2. *Strike slip.* Slippage takes place in a horizontal direction.
   a. *Left lateral fault.* As seen from one rock bed, the other rock bed slips toward the left (Fig. 1-4*c*).
   b. *Right lateral fault.* As seen from one rock bed, the other rock bed slips toward the right.

Actual faults are often a combination of the four types of slippages.

A fault that emerges at the surface of the earth because of an earthquake is called an *earthquake fault.* Earthquake faults are not formed by deep earthquakes.

The best-known example of an earthquake fault is the 300-km-long strike slip of 6.4 m at the San Andreas fault, which caused the San Francisco earthquake of 1906 ($M = 8.3$, where M is the magnitude on the Richter Scale shown in Sec. 1.1.3.2). During the Imperial Valley earthquake of 1940 ($M = 7.1$), a 60-km-long right lateral fault was created with a maximum slip of 5 m (see Fig. 1-12 below).

One of the most famous faults in Japan was created by the Nobi earthquake ($M = 8.4$) in 1891. It is 80 km long and showed a 6-m vertical slip and a 2- to 4-m horizontal slip. The Kansu earthquake of 1920 ($M = 8.5$) in China created a left lateral fault 200 km long.

Generally speaking, the length and width of a fault are comparable when the fault is created by relatively small earthquakes of $M < 6$ (see Sec. 1.1.3.2), but such earthquakes rarely form earthquake faults. Faults are longer when earthquakes are greater (Sec. 1.1.3.2).

Faults are causes rather than results of earthquakes. An earthquake is caused by a fault in the following ways:

1. Strain that has accumulated in the fault for a long period of time reaches its limit (Fig. 1-5*a*).

2. Slip occurs at the fault and causes a rebound (Fig. 1-5*b*).

3. A push-and-pull force acts at the fault (Fig. 1-5*c*).

4. This situation is equivalent to two pairs of coupled forces suddenly acting (Fig. 1-5*d*).

5. This action causes radial wave propagation.

The moment of each couple is called the *earthquake moment* or *seismic moment* (Kasahara, 1981). The seismic moment is defined as the rigidity of the rock times the area of faulting times the amount of slip. Recently it has been used as a measure of earthquake size (see Sec. 1.1.3.2).

Active faults are faults that have undergone deformation for the past several hundred thousand years and will continue to do so in the future. They have been found by geological and topographical surveys and aerial photographs. Since earthquakes often occur at active faults, when designing an important structure such as a nuclear power plant to resist seismic forces, the distance from a nearby active fault or faults to the building site, seismic activity, and other factors related to the fault are taken into account in predicting seismic motion of the ground.

The famous San Andreas fault in California reveals itself on land between Point Arena and the Gulf of California. A right lateral fault, it occurs where the Pacific plate slips to the north against the North American plate. It caused the Fort Tejon earthquake (1857), the San Francisco earthquake (1906), and other earthquakes.

Average slip velocity at an active fault varies. The highest velocities,

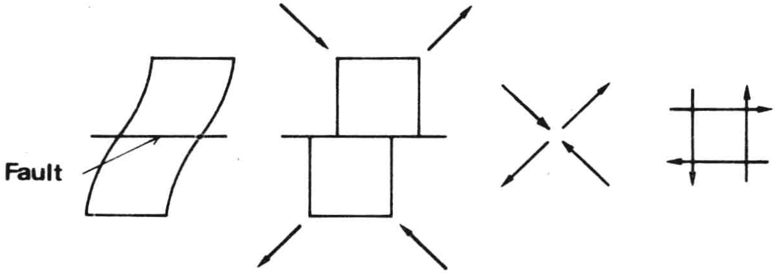


Figure 1-5 Earthquake mechanism. *(a)* Before slip. *(b)* Rebound due to slip. *(c)* Push-and-pull force. *(d)* Double couple.

those of the San Andreas fault and the Nankai trough of Japan, are 10 to 100 mm/year. A slippage of 3 m during one earthquake therefore means that earthquakes occur at intervals of 30 to 100 years at these faults. Some active faults, such as the San Andreas fault, are always moving; others, such as some faults in Japan, move only when an earthquake occurs.

1.1.2 Earthquakes and Seismic Waves

1.1.2.1 Epicenter The point where the seismic motion originates is called the *focus, center,* or *hypocenter* of the earthquake; and the projection of the focus onto the surface of the earth is the *epifocus* or *epicenter.* The distances from the focus and the epicenter to the point of observed ground motion are called the *focal distance* and the *epicentral distance,* respectively.

Seismic destruction propagates from the focus through a limited region of the surrounding earth body, which is called the *focal region.* The larger the earthquake, the larger the focal region.

Earthquakes are classified as shallow, intermediate, and deep, depending on the depths of their foci. Limiting depths are often set at 70 km and 300 km.

1.1.2.2 Seismic Waves Two types of seismic wave travel from the foci in the earth body: the *body wave* and the *surface wave.* The body wave, which propagates in an infinite continuum, is a twofold P wave and S wave. The P wave is often called the longitudinal wave or the compressive wave; it propagates in the same direction as its own vibration. The S wave is called the transverse wave or the shear wave; it propagates in a direction perpendicular to its vibration.

The propagation velocities of the P wave, V_p, and the S wave, V_s, are expressed as follows:

$$V_p = \left[\frac{E}{\rho}\,\frac{1-\nu}{(1+\nu)(1-2\nu)}\right]^{\frac{1}{2}} \tag{1-1}$$

$$V_s = \left(\frac{G}{\rho}\right)^{\frac{1}{2}} = \left[\frac{E}{\rho}\,\frac{1}{2(1+\nu)}\right]^{\frac{1}{2}} \tag{1-2}$$

where E = Young's modulus
G = shear modulus
ρ = mass density
ν = Poisson ratio

For any material $V_p > V_s$, and if the Poisson ratio for the earth body is taken to be 0.25, then $V_p = \sqrt{3}\ V_s$ is obtained from Eqs. (1-1) and (1-2). Near the surface of the earth, V_p = 5 to 7 km/s and V_s = 3 to 4 km/s.

Surface waves propagate on the earth's surface and are detected more often in shallow earthquakes. They are mainly classified into two kinds: L waves (Love waves) and R waves (Rayleigh waves). An L wave takes place in stratified formations and vibrates in a plane parallel to the earth's surface and perpendicular to the direction of wave propagation. An R wave vibrates in a plane perpendicular to the earth's surface and exhibits an elliptic movement. Its velocity is smaller than but nearly equal to that of an S wave.

A P wave arrives at an observation station earlier than an S wave because its velocity is higher. In the earthquake accelerograms of Fig. 1-6 the P wave is recorded for some time before the S wave arrives.

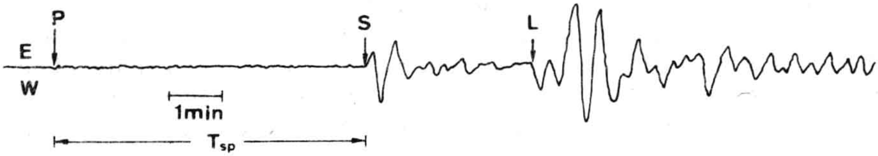


Figure 1-6 Earthquake accelerogram. The arrivals of the P, S, and surface (L) waves are marked. Time increases from left to right. *(Courtesy of T. M. Mikumo.)*

The time interval between the arrival at the observation station of a P wave and an S wave is called the *duration of preliminary tremors,* T_{sp}. If the two waves travel along the same route and have a constant velocity, the following equation gives the duration of the preliminary tremors:

$$T_{sp} = \left(\frac{1}{V_s} - \frac{1}{V_p}\right)\Delta \qquad (1\text{-}3)$$

in which Δ is the distance from the focus to the observation point. This means that the epicenter can be located and the depth of the focus can easily be obtained graphically if earthquake records are made at least at three different observation points.

1.1.3 Scale and Intensity of Earthquakes

1.1.3.1 Intensity Scale An *intensity scale* is the scale of ground-motion intensity as determined by human feelings and by the effects of ground motion on structures and on living things. It is graded according to intensity.

Proposed intensity scales included the Gastaldi Scale (1564) and the Pignafaro Scale (1783). The Rossi-Forel Scale (1883), which has 10 grades, is still used in some parts of Europe. The Mercalli-Cancani-Sieberg Scale, developed from the Mercalli (1902) and Cancani Scales (1904), is still widely used in western Europe. In 1931 F. Neumann modified the Mercalli-Cancani-Sieberg Scale, proposing a 12-grade Modified Mercalli (MM) Scale, which has now been widely adopted in North America and other parts of the world (see Table 1-1). Other intensity scales are the 12-grade Medvedev-Sponheuer-Karnik (MSK) Scale (1964), which is intended to unify intensity scales internationally, and the 8-grade scale of the Japanese Meteorological Agency (JMA).

Intensity scales are established on the basis of visible phenomena and human feelings as indicated in Table 1-1. Therefore they bear no specific relation to the maximum acceleration of ground motion, and correlation among different intensity scales is not necessarily clear. Figure 1-7 is one attempt to correlate intensity scales (AIJ, 1981).

If seismic intensities at various points for a small earthquake are plotted on a map, the ideal isoseismal pattern shows a bell shape. The shape will be as in Fig. 1-8 if the causative fault is several hundred kilometers long (Housner, 1969). In reality, however, the isoseismal pattern is dependent upon conditions at the epicenter, the route of the seismic wave from the focus to the observation station, geological conditions at the observation points, and other influences, and its shape is more complex.

1.1.3.2 Magnitude The size of an earthquake is closely related to the amount of energy released. The magnitude M defined by Richter in 1935

TABLE 1-1 Abridged Modified Mercalli Earthquake Intensity Scale

Intensity value	Description
I	Not felt except under exceptionally favorable circumstances
II	Felt by persons at rest
III	Felt indoors; may not be recognized as an earthquake
IV	Windows, dishes, and doors disturbed; standing motor cars rock noticeably
V	Felt outdoors; sleepers wakened; doors swing
VI	Felt by all; walking unsteady; windows and dishes broken
VII	Difficult to stand; noticed by drivers; fall of plaster
VIII	Steering of motor cars affected; damage to ordinary masonry
IX	General panic; weak masonry destroyed, ordinary masonry heavily damaged
X	Most masonry and frame structures destroyed with foundations; rails bent slightly
XI	Rails bent greatly; underground pipes broken
XII	Damage total; objects thrown into the air