高校土木工程专业规划教材

Seismic Design of Building Structures

建筑结构抗震设计

ZHOU Ying　LU Zheng　DAI Kaoshan　JIANG Jiafei　SHAN Jiazeng

周颖　鲁正　戴靠山　江佳斐　单伽锃

中国建筑工业出版社

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This book introduces the fundamental knowledge of seismic design of building structures, from seismology to earthquake engineering. It introduces the basic concepts of seismic design with several engineering examples in China to facilitate readers to understand the concepts in the design codes and its applications.

This book can serve as a guide for instructors, graduate students and practicing engineers. We hope it will contribute to the teaching of earthquake engineering and its applications to practice, as well as to the formulation and evolution of research programs.

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Preface

It is recognized that seismic design of building structures is a multi-disciplinary and highly integrated course; consequently, it is essential to work together with colleagues from several fields to make the essence of these subjects involving seismic design of structures more accessible to readers. Furthermore, the seismic design in China is based on three earthquake levels, which is unique to other countries. In view of these, the authors in Tongji University edited the book "*Seismic Design of Building Structures*", based on the experiences of over 10 years' study, education and engineering practice on earthquake engineering.

This book is chief edited by Ying Zhou. The 9 chapters and contributors are:

- Chapter 1. Fundamental Knowledge of Earthquakes and Ground Motions (Jiazeng SHAN)
- Chapter 2. Site, Subsoil and Foundation (Kaoshan DAI)
- Chapter 3. Structural Seismic Response of Single-Degree-of-Freedom and Multi-Degree-of-Freedom Systems (Zheng LU)
- Chapter 4. Seismic Action and the Basic Principles of Seismic Design for Building Structures (Ying ZHOU)
- Chapter 5. Seismic Design of Reinforced Concrete Building Structures (Ying ZHOU)
- Chapter 6. Seismic Design of Masonry Building Structures (Kaoshan DAI)
- Chapter 7. Seismic Design of Steel Building Structures (Zheng LU)
- Chapter 8. Seismic Design of Non-structural Elements (Jiafei JIANG)
- Chapter 9. Introduction to Seismic Isolation and Energy Dissipation for Building Structures (Ying ZHOU)

The highlights of this book is the integration of theoretical description and engineering practice, focusing on the elaboration of basic concepts, and illustration of the detailed examples. We hope that it can help readers understand the basic theory and fundamental method in seismic design, as well as use the codes to do seismic design for various types of building structures.

ZHOU Ying, LU Zheng, DAI Kaoshan
JIANG Jiafei, SHAN Jiazeng
August, 2016

Contents

Chapter 1 Fundamental Knowledge of Earthquakes and Ground Motions

1.1 Earthquakes

Earthquakes are a natural phenomenon. Approximately 5,000,000 earthquakes occur each year around the world. Only 1% of these earthquakes can be felt, known as *felt earthquakes*, because most earthquakes occur at great depths or the released energy is relatively small. Intense earthquakes that cause disasters occur less frequently, approximately dozens of times each year. Shaking and ground rupture are the principal effects of earthquakes, primarily resulting in relatively severe damage to buildings, human injuries and loss of life. Furthermore, earthquakes can cause fires, floods, landslides, avalanches and tsunamis, which can be disastrous to human beings.

1.1.1 Structure of the earth

To better understand the cause and development of earthquakes, the structure of the earth is briefly presented.

The earth is an oblate spheroid with an average radius of 6370 km, an equatorial radius of 6378 km and a polar radius of 6357 km. The earth is generally divided into three layers based on chemical or physical properties: crust, mantle and core. (Figure 1-1)

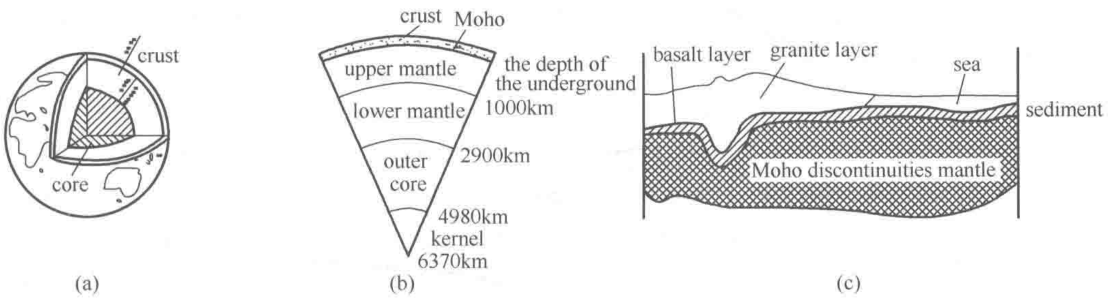

Figure 1-1 The earth section and crust section

(a) The earth section; (b) laminar structure; (c) The crust section

(1) Crust

The crust, which is the outermost layer, is comprised of various rocks. The crust is separated from the mantle by the Mohorovičić scontinuity (or Moho). The thickness of the crust varies: 16～40 km on land and thicker at higher altitudes, reaching 70 km on Chinese Tibet Plateau and in Tianshan District. It is considerably thinner under the oceans, averaging 10～16 km, and the thinnest part of the crust is approximately 5 km.

The continental crust is primarily comprised of granite and basalt, whereas the oceanic crust is mostly composed of basalt. The vast majority of earthquakes occur in this layer.

(2) Mantle

The mantle extends to a depth of 2895 km and comprises approximately 5/6 of the earth's volume. The core-mantle boundary is known as the Gutenberg discontinuity. The mantle is assumed to be composed of peridotite, which is an ultramafic rock. The structure of matter is heterogeneous in the upper mantle and homogeneous in the lower mantle. Because shear waves propagate through the mantel, it has been suggested that the mantle should be solid.

(3) Core

The core extends from the Gutenberg discontinuity to the center of the earth with a radius of 3500 km. It is composed of two layers: the inner and outer cores. The core is generally believed to be primarily composed of iron and nickel. The outer core is suggested to be liquid because no seismic waves have been observed in this region, and the inner core may be solid.

Both density and temperature increase with increasing depth in the earth. The pressure at the top of the mantle is approximately 883 MPa (9×10^3 kg/cm^2), whereas that at the center of the core reaches 36284 MPa (37×10^5 kg/cm^2).

1.1.2 Earthquake generation process

An earthquake is a sudden release of energy in the earth caused by various forces, e. g. a rock burst, collapse, or volcanic eruption, that results in ground motions. The position where an earthquake originates is the hypocenter. Although the hypocenter has a certain range, it is always considered a point in seismology because it is relatively small when compared to other aspects of seismology. The point on the earth's surface that is directly above the hypocenter is the epicenter. The distance between the hypocenter and the epicenter is known as the focal depth. Earthquakes occurring at a depth of less than 60 km are classified as 'shallow-focus' earthquakes, whereas those with a focal-depth between 60 km and 300 km are commonly termed 'mid-focus' or 'intermediate-depth' earthquakes. Deep-focus earthquakes occur at considerably greater depths, i. e. exceeding 300 km.

The majority of earthquakes are shallow-focus earthquakes, with a focal depth ranging from 5 km to 20 km, whereas intermediate-depth earthquakes occur less frequently, and deep-focus earthquakes occur rarely. A deep-focus earthquake occurred in the eastern region of Jilin province in northeast China. Generally, for the same earthquake magnitude, an earthquake with a smaller focal depth results in a larger extent of damage over a small area, whereas an earthquake with a greater focal depth results in less damage but over a larger spatial area. An earthquake with a focal depth greater than 100 km typically does not cause damage at the surface.

1.1.3 Causes of earthquakes and earthquake fault types

Earthquakes may result from numerous natural and human-induced phenomena, including meteoric impacts, volcanic activity, underground nuclear explosions and rock stress changes induced by the filling of large manmade reservoirs. However, the vast majority of damaging earthquakes originate at or are adjacent to the boundaries of crustal tectonic plates due to the relative deformations at the boundaries.

A coherent global explanation for most earthquakes can be given in terms of plate tectonics, which is now considered to be the most reliable theory. The relative motion between the plates leads to increasing stress and stored strain energy in the volume around the fault surface. This pattern continues until the stress rises to a sufficient level, driving a fracture propagation along a fault plane, which releases the stored energy. The energy is propagated as a combination of radiated elastic strain seismic waves, frictional heating of the fault surface and cracking of the rock, which causes an earthquake. A fault that emerges at the surface of the earth because of an earthquake is known as an earthquake fault. Faults are causes rather than the results of earthquakes. Tectonic earthquakes often occur at existing faults because of stress concentration and low-strength rock.

Faults are classified in terms of the direction and nature of the relative displacement of the earth at the fault plane. There are three primary types of earthquake faults: normal, reverse (thrust) and strike-slip. Normal and reverse faults are examples of dip-slip, where the displacement along the fault is in the direction of the dip, and the movement on them involves a vertical component. A normal fault (Figure 1-2(a)) is one in which the rock above the inclined fault surface moves downward relative to the underlying crust. Furthermore, faults with nearly vertical slip are included in this category. A reverse fault (Figure 1-2(b)) is one in which the crust above the inclined fault surface moves upward relative to the block below the fault. Strike-slip faults (Figure 1-2(c)) involve lateral displacements of the rock, i. e. parallel to the strike. Several earthquakes are due to movement on the faults that have components of all three fault types.

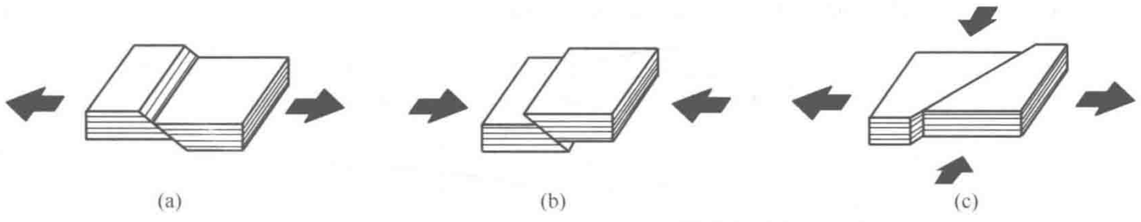

Figure 1-2 Types of fault movement
(a)normal fault; (b)reverse fault; (c)lateral fault

1.2 Seismic waves

The energy released by an earthquake from the focal point is propagated by two wave types: the body wave and the surface wave. These seismic waves are similar to analogous waves in air, water, and gelatin in several important aspects.

1.2.1 Body waves

Body waves, which originate at the rupture zone and travel within a body of solid rock, include P waves (primary or dilatation waves) and S waves (secondary or shear waves).

The P wave involves particle movement parallel to the direction of wave propagation, i. e. as it spreads out, it alternately pushes (compresses) and pulls (dilates) the rock, as indicated in Figure 1-3(a). These P waves, which are similar to sound waves, are able to travel through both solid rock such as granite mountains, and liquid material such as volcanic magma or oceans.

The S wave involves particle movement perpendicular to the direction of propagation, producing an up-and-down and side-to-side motion that shakes the ground vertically and horizontally at right angles to the direction of propagation, as indicated in Figure1-3(b). This S wave motion causes major damage to structures. S waves cannot propagate in liquid, such as the oceans, and their amplitude is significantly reduced in liquefied soil.

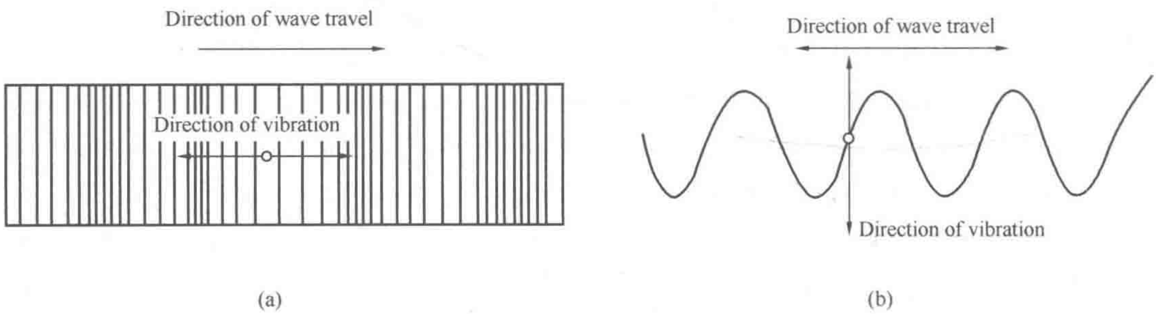

Figure 1-3 Diagrammatical sketch of the propagation of body waves
(a) P waves; (b) S waves

The propagation velocities of the P and S waves depend on the density and elastic properties of the rock and soil that they pass through, which can be expressed as follows:

$$V_p = \sqrt{\frac{E(1-\gamma)}{\rho(1+\gamma)(1-2\gamma)}} = \sqrt{\frac{\lambda + 2G}{\rho}} \tag{1-1}$$

$$V_s = \sqrt{\frac{E}{2\rho(1+\gamma)}} = \sqrt{\frac{G}{\rho}} \tag{1-2}$$

where V_p —the velocity of the P wave;

V_s —the velocity of the S wave;

E —Young's modulus;

γ —the Poisson ratio;

ρ —the mass density of the medium;

G —the shear modulus;

λ —the Lame constant: $\lambda = \dfrac{\gamma E}{(1+\gamma)(1-2\gamma)}$.

Using Formula (1-1) and Formula(1-2), the ratio of V_p to V_s can be obtained as follows:

$$\frac{V_p}{V_s}=\sqrt{\frac{2(1-\gamma)}{1-2\gamma}} \tag{1-3}$$

For typical materials, $V_p > V_s$. Thus, during earthquakes, P waves travel faster than S waves. For example, if the Poisson ratio for the earth body is assumed to be 0.25, then $V_p = \sqrt{3}V_s$.

The difference in the time of arrival of the P and S waves at an observation point is determined by the distance to the epicenter of the earthquake. The difference in time is easily obtained using a strong-motion earthquake accelerogram. The instrument producing the accelerogram is triggered to start when the P wave arrives, which produces a small acceleration. The acceleration sharply increases when the S wave arrives.

Based on Formule (1-1)~(1-3), the parameters of the material can be obtained. For example, using the measured V_p and V_s, the Poisson ratio can be calculated using Eq. (1-3). If the mass density ρ and (E, G), (γ, λ), or (V_p, V_s) are known, then the other two sets of parameters can be obtained. These parameters are extremely important in earthquake engineering research and applications.

1.2.2 Surface wave

Surface waves primarily travel at or near the ground surface. They are generally considered to be the resultant wave formed by the reflection of body waves at the stratum interface. Surface waves are generally known as either Rayleigh waves or Love waves.

Rayleigh waves move both vertically and horizontally in a vertical plane pointed in the direction that the waves are travelling and exhibit elliptic movement, which is indicated in Figure 1-4(a). Rayleigh waves appear far from the epicenter. They decrease exponentially in amplitude as the distance from the surface increases.

The particle motion of a Love wave forms a horizontal line perpendicular to the direction of propagation, which is indicated in Figure 1-4(b). Because of the coupling of the horizontal vibration with the propagation of the wave, there is a horizontal torsional component in a Love wave, which is one of the essential characteristics of a Love wave.

Surface waves travel relatively slowly; S waves travel faster, and P waves are the fastest. Therefore, in the seismic record, P waves arrive first, then S waves, and surface waves arrive after body waves. The most intense ground motion appears when S waves or surface waves arrive.

1.2.3 Ground motion and its characteristics

Seismic waves released from the hypocenter result in ground motions. The ground motion can be represented as a function of the acceleration, velocity or displacement of the particles on the ground in terms of time. The characteristics of the seismic acceleration time history, which is widely used in earthquake engineering applications, are listed below.

1. Peak ground acceleration

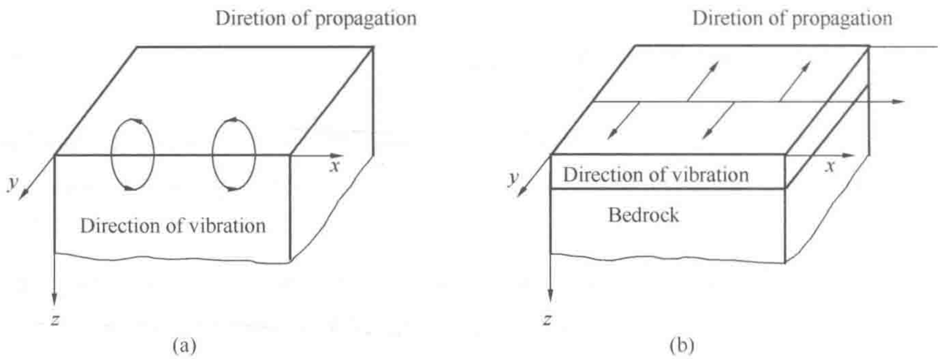

Figure 1-4 Body wave propagation

(a) Rayleigh wave; (b) Love wave

The peak ground acceleration primarily influences the vibration amplitudes. It has been extensively used to scale earthquake design spectra and acceleration time histories.

2. Frequency content

The frequency content of ground motions can be examined by transforming the motion from a time domain to a frequency domain using the Fourier transform. The power spectral density, response spectrum and Fourier spectrum are commonly used to characterize the frequency content. The ground motion has a long period component for soft soil and a short period component for stiff soil, which is extremely useful in the seismic design of structures.

3. Duration

The duration of strong motion affects structural damage, primarily after the structure cracks. After a structure cracks, it will most likely collapse if it suffers from longer duration ground motion. Therefore, the ground motion duration is one of the crucial parameters in studying the collapse-resistance of structures.

1.3 Earthquake magnitude and intensity

The severity of an earthquake can be described by both its magnitude and intensity.

1.3.1 Earthquake magnitude

The magnitude characterizes the size of an earthquake by indirectly measuring the energy released. There are three types of magnitude scales: local magnitude scale M_L, surface wave magnitude M_s, and body wave magnitude M_s.

In the 1930s, C. F. Richter defined the magnitude of a local earthquake as the logarithm to base ten of the maximum amplitude in microns (10^{-6} meters) recorded on a Wood-Anderson seismograph located at a distance of 100 km from the epicenter of the earthquake. However, a standard seismograph is not always set at a point 100 km from the epicenter, thus, the following formula can be used:

$$M_L = \log A - \log A_0 \tag{1-4}$$

where A——the maximum amplitude of the seismic record in μm;

A_0——the maximum amplitude of a standard seismic record at the same epicenter distance.

The local magnitude scale and the magnitude of an earthquake can be identified as follows:

$$M_L = \log A_\mu + R(\Delta) \quad (1\text{-}5)$$

where A_μ——the maximum amplitude of the local seismic record in μm, which is the arithmetic mean of the two horizontal components; the amplitudes of the two components do not have to be measured at the same time.

Furthermore, $R(\Delta)$ can be determined as follows:

$$R(\Delta) = \log V_0(T) - \log A_0 - 3 \quad (1\text{-}6)$$

where $V_0(T)$——the amplification in the maximum amplitude period recorded by the standard seismograph;

$\log A_0$——the same as that in Eq. (1-4).

The surface wave magnitude M_S used in China can be obtained as follows:

$$M_S = \log(A/T) + \sigma(\Delta) + C \quad (1\text{-}7)$$

where A——the maximum displacement amplitude of the surface waves in μm, which is vector sum of the two horizontal components;

T——the period corresponding to the amplitude A;

$\sigma(\Delta)$——a function of the starting calculation;

C——the calibration value of the station.

For deep-focus earthquakes, only small surface waves can be recorded; hence, Gutenberg suggested using the body wave magnitude. The body wave magnitude used in China can be obtained as follows:

$$M_B = \log(A/T) + Q + S \quad (1\text{-}8)$$

where A——the maximum amplitude of the body wave magnitude in μm, in which the horizontal component is the vector sum of the two horizontal components;

T——the period corresponding to the amplitude A;

Q——the function of the starting calculation;

S——the calibration value of the station.

Theoretically, M_L, M_S and M_B should be equivalent for an earthquake. However, system deviations are observed for different magnitudes. The empirical equations are as follows:

$$M_S = 1.13M_L - 1.08 \quad (1\text{-}9)$$

$$M_B = 0.63M_S + 2.5 \quad (1\text{-}10)$$

The Chinese earthquake department has selected M_S as the reported earthquake magnitude for convenience.

Generally, earthquakes with magnitudes less than 2, which are called micro-earthquakes, can barely be felt by people. Earthquakes with magnitudes between 2 and 4, which are known as sensible earthquakes, can be felt by humans. Earthquakes with magnitudes greater than 5, which are known as destructive earthquakes, can cause damage. Lastly, earthquakes with magnitudes greater than 7 are known as strong earthquakes.

1.3.2 Earthquake intensity

Earthquake intensity represents the severity of the shaking resulting from an earthquake. It indicates the local effects and the potential for damage produced by an earthquake on the earth's surface that affects humans, animals, structures, and natural objects.

The proposed intensity scale includes a 12-grade Modified Mercalli Scale (MMS), which is widely used in the USA, Canada and South America, a 12-grade Medvedev-Sponheuer-Karnik (MSK) Scale (1964), which is primarily used in Europe, and the 8-grade scale of the Japanese Meteorological Agency (JMA) (1949). In China, a 12-grade intensity scale is used, which was issued in 1999 and revised in 2008 (Table 1-1).

Chinese seismic intensity scale (2008) **Table 1-1**

Intensity	Sensed by people on the ground	Extent of building damage			Other damage	Horizontal ground motion	
		Type	Damage	Mean damage index		Peak acceleration (m/s^2)	Peak speed (m/s)
1	Insensible	—	—	—	—	—	—
2	Sensed by very few people who are indoors and not moving	—	—	—	—	—	—
3	Sensed by few people who are indoors and not moving	—	Slight rattle of doors and windows	—	Slight swinging of suspended objects	—	—
4	Felt indoors by many and outdoors by few during the day; at night, some people are awakened	—	Doors and windows disturbed	—	Obvious swinging of suspended objects; dishes disturbed	—	—
5	Felt by nearly everyone; many awakened	—	Windows and doors disturbed; walls cracking; roof tiles and chimney bricks falling	—	Dishes fall down; some break	0.31(0.22~0.44)	0.03 (0.02~0.04)

continued

Intensity	Sensed by people on the ground	Extent of building damage			Other damage	Horizontal ground motion	
		Type	Damage	Mean damage index		Peak acceleration (m/s^2)	Peak speed (m/s)
6	Felt by all; many frightened	*A*	Slight damage; most in good condition	0.00～0.11	Cracks in river banks and soft soil; occasional sand and water bursting from saturated sand layers; cracks on some standalone chimneys	0.63 (0.45～0.89)	0.06 (0.05～0.09)
		B	Very slight damage; most in good condition				
		C	Very slight damage; most in good condition	0.00～0.08			
7	Many frightened to run outdoors; felt by bicycle riders and persons in cars	*A*	Slight damage	0.09～0.31	Collapse of river banks; frequent sand and water bursting from saturated sand layers; many cracks in soft soils; moderate destruction of standalone chimneys	1.25 (0.90～1.77)	0.13 (0.10～0.18)
		B	Very slight damage				
		C	Very slight damage, most in good condition	0.07～0.22			
8	Hard to walk	*A*	Mostly moderate damage	0.29～0.51	Cracks appear in hard, dry soils; severe destruction of most standalone chimneys; tree tops break; deaths caused by building destruction	2.50 (1.78～3.53)	0.25 (0.19～0.35)
		B	Mostly slight damage				
		C	Mostly slight damage	0.20～0.40			

continued

Intensity	Sensed by people on the ground	Extent of building damage			Other damage	Horizontal ground motion	
		Type	Damage	Mean damage index		Peak acceleration (m/s^2)	Peak speed (m/s)
9	Moving people fall down	*A*	Extensive severe damage	0. 49~0. 71	Many cracks in hard, dry soils; possible cracks and dislocations in bedrock; frequent landslides and collapses; collapse of many standalone chimneys	5(3. 54~7. 07)	0. 5(0. 36~0. 71)
		B	Few collapses and moderate damage				
		C	Few collapses and slight damage	0. 38~0. 60			
10	Bicycle riders may fall; people in an unstable state may fall; sense of being thrown upward	*A*	Many collapses	0. 69~0. 91	Cracks in bedrock and earthquake fractures; destruction of bridge arches founded in bedrock; foundation damage or collapse of most standalone chimneys	10(7. 08~14. 14)	1 (0. 72~1. 41)
		B	Several collapses				
		C	Extensive severe damage	0. 58~0. 80			
11		*A*	Nearly all buildings collapse	0. 89~1. 00	Earthquake fractures extend a long way; many bedrock cracks and landslides	—	
		B					
		C		0. 78~1. 00			

continued

Intensity	Sensed by people on the ground	Extent of building damage			Other damage	Horizontal ground motion	
		Type	Damage	Mean damage index		Peak acceleration (m/s^2)	Peak speed (m/s)
12		*A*	Nearly all buildings collapse	1.00	Drastic change in landscape, mountains, and rivers	—	
		B					
		C					

Notes:

(1) Buildings in the table include the following three types:

Type *A*: wooden structures and antique structures built by soil, stone and brick walls

Type *B*: multi-story masonry structures without seismic resistance

Type *C*: multi-story masonry structures with seismic resistance for an intensity of 7

(2) The peak ground acceleration and peak ground velocity are reference values, and the values in parentheses denote the corresponding range.

Note for the intensity ratings:

(1) Intensities of 1～5 depend primarily on human feeling; intensities of 6～10 depend primarily on building damage; and intensities of 11 and 12 depend on the building damage and ground phenomena.

(2) General buildings include wooden buildings, antique buildings built by soil, stone and brick walls, and new masonry buildings. The extent of earthquake damage and the earthquake damage index in Table 1-1 can be increased or decreased for high-quality or low-quality structures based on specific conditions.

(3) An earthquake damage index of 0 indicates that a building is in perfect condition, whereas index of 1 indicates it will be destroyed. The average earthquake damage index is the sum of each earthquake damage index multiplied by the corresponding destruction rate.

(4) The severity of earthquake damage can be classified as follows:

a) Almost no structure is in good condition, cracks occur, and the structure can be used without repairs. The earthquake damage index ranges 0～0.10.

b) Slight- localized damaged, cracks occur, and the structure may continue to be used with small repairs or without repair. The earthquake damage index ranges 0.10～0.30.

c) Moderate-structural damages occurs, and the structure can continue to be used with repair. The earthquake damage index ranges 0.30～0.55.

d) Severe-severe structural damages, localized collapse, and difficult to repair. The earthquake damage index ranges 0.55～0.85.

e) Destroyed-severe structural damage, structural collapse, and impossible to repair. The earthquake damage index ranges 0.85～1.0.