CHAPTER 6: THE EARTH TREMBLES

SESSION 1: SEISMIC WAVES

Topic 1.1 : Seismic Waves

In nature different forms of energy radiation occur. Their behavior is stretched in Fig.1.1-1.

Body Waves
Two types of wave motion through physical bodies like the Earth's interior can be distinguished: longitudinal (P); transverse (S).

Longitudinal or compression waves
In longitudinal waves, the direction of particle motion coincides with the direction of waves. The longitudinal wave is also called *P-wave* (from primary phase).The velocity of such waves is the following:

$$a = \sqrt{(E(1-v) / \delta(1+v)(1-2v))}$$

where:

E = Young's modulus;
v = Poisson's ratio;
δ = density.

Transverse or shear waves
In transverse waves the direction of particles is orthogonal to the direction of advance and the velocity is:

$$\beta = \sqrt{(E / 2\delta(1+v))}$$

The transverse wave is called *S-wave* (from secondary phase), a *SV-wave* when vertically polarized and an *SH-wave* when horizontally polarized.

Surface Waves
At the surface there are ground movements which rapidly faint out deeper underground. These are termed surface waves. Two types can be distinguished: the Rayleigh wave; the Love wave.

Rayleigh Waves
The surface wave in homogeneous ground and along its free surface is named a Rayleigh wave. Particle motion describes an ellipse in the vertical plane, parallel with the direction of Rayleigh wave propagation. Ellipse has its major axis in the vertical direction and its minor axis in the horizontal direction. The propagation velocity of Rayleigh wave, v_R, is slightly lower than the propagation velocity of S-waves v_S.
The Rayleigh waves are caused by longitudinal or transverse waves emitted from the hypocenter. However, they are not produced in the vicinity of the epicenter.

Love waves
The Love waves are a type of surface waves which emerge only when a soft layer is overlaying a stiff substratum. Through the soft surface layer, they propagate as plane waves, but in the substratum they rapidly become faint. Love waves propagate in horizontal plane with direction of the particle motion being transversal to the propagation direction.

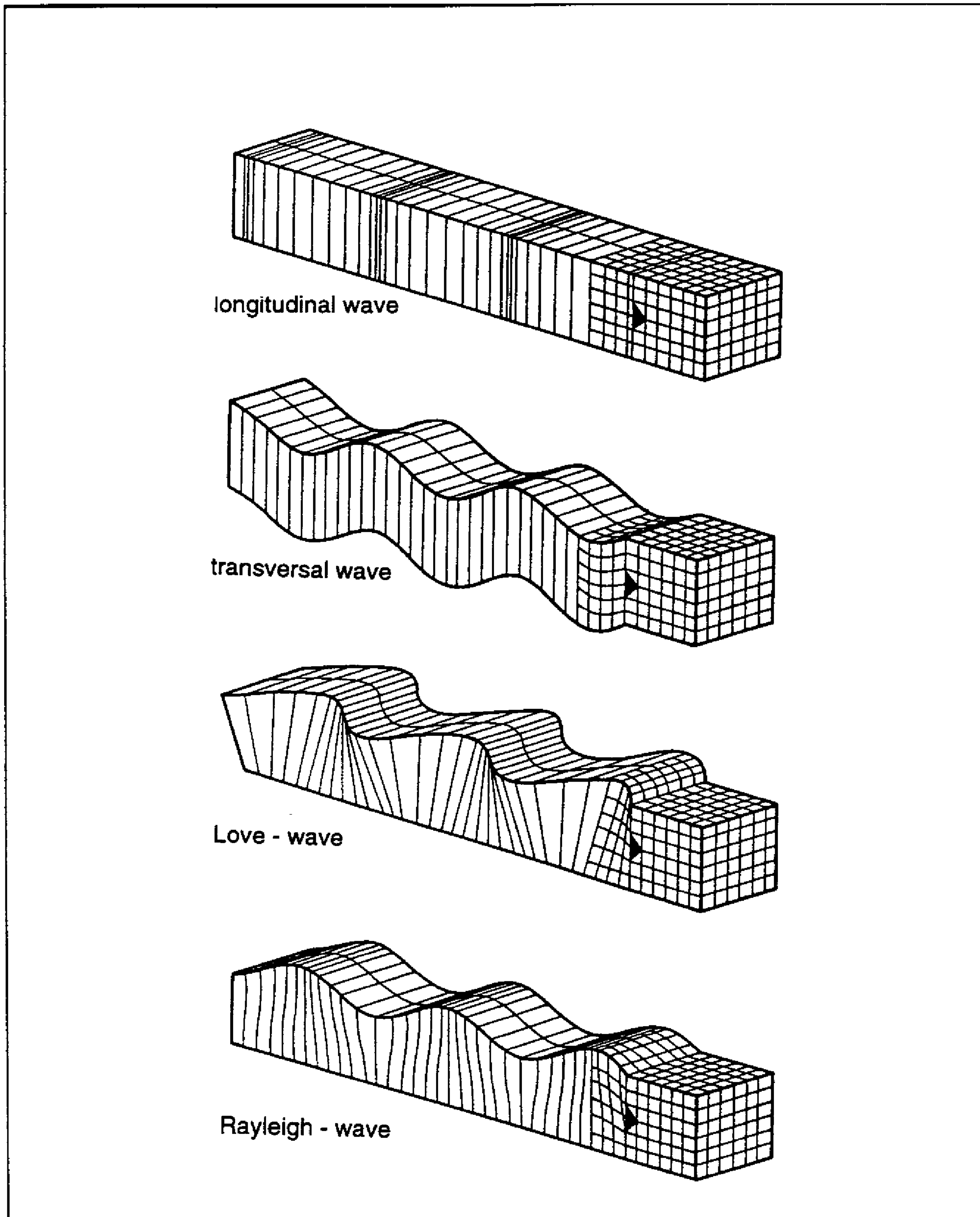


Figure 1.1 Particle motion for the propagation of the four different types of seismic waves: longitudinal or P-waves, transversal or S-waves. Love- and Rayleigh-waves.

Seismic waves

SESSION 2: STRUCTURE OF THE EARTH

Topic 2.1 : Structure of the Earth

The planet Earth is a living body that constantly is undergoing physical processes of change. It moves, changes its surface relief, vibrates and produces flows of water, air and earth that constitute hazards for its inhabitants.

Composition
The Earth is an approximately spherical body measuring about 6,400 km in radius. Its internal structure has been deduced from various clues; comparing the vibrations at different points on the Earth's surface at the time of an earthquake is an important method of investigation.
According to such investigations, the Earth generally consists of three layers of different nature: the core or centrosphere, the mantle, and the crust. The core comprises the central part of the Earth (Figure 2.1), and is spherical with a radius of 3,500 km. Since it does not transmit transverse waves, at least its surface portion is considered to be liquid. The mantle envelopes the core and is 2,900 km in thickness.

The Earth's crust differs in composition and thickness in its oceanic and continental (including continental shelf) parts. The crust under the oceans is approximately 5 km in thickness. The crust in the continental areas consists of two layers with a thickness of mostly 30 km which is increasing up to 60 km under high mountain ranges.

Temperatures and Pressures
The temperature of the Earth increases with depth. The rate of temperature rise is about 30°C/km within the surface portion of the Earth, but this rate decreases with the increase of depth. At the bottom of the crust the temperature is 150°- 250°C in the oceanic crust and 300°- 800°C in the continental crust.

In the mantle, the temperature is 1,000°- 1,500°C at 700 km, which is the greatest depth at which earthquakes are thought to originate, and 4,000°- 5,000°C at the bottom portion.

However, these temperatures are average; actual temperatures vary, sometimes sharply, from the average values depending on the regional geophysical characteristics.

Considering the physical properties of the mantle and the temperature distribution in it, there should be thermal conveyance due to convection in the mantle. However, its mechanism and scale is hardly to determine in situ. But thermodynamic modelling carried out in the last years gave valuable insight into such processes.

Velocities of seismic waves
The velocity of a longitudinal seismic wave is about 6.0 km/sec in a granitic part of the crust and about 6.8 km/sec in a basaltic part. In the mantle, it is about 8 km/sec in the upper part and about 3 km/sec in the lower. Near the boundary between the Earth's crust and the mantle there is a plane at which the velocities of seismic waves undergo discontinuous changes, called the Mohorovicic discontinuity.

In the layer of the upper mantle 70-250 km in depth, the velocity of seismic waves is relatively low. This low speed layer is called the asthenosphere. It is thought that the lithosphere which is about 100 km thick, drifts on the surface of the mantle using the asthenosphere as a lubricant.

In diluvial and alluvial deposits on the surface, the velocity is extremely different from deep underground. The values in Table 2.1 give probable velocities of transverse or shear waves in dependence on the depth of deposit. Note that the upper soil layers are responsible for site amplification effects.

Since earthquakes are vibrations produced at the surface of the Earth through disturbances in the Earth's interior, the vibrations actually observed depend on the structure along the propagation path. Thus, interpretation of such patterns serves in reverse as a means of probing the internal structure of the Earth.

EARTHQUAKES

Topic 3.1 : The framework of plate tectonics

The theory of plate tectonics explains the dominating earthquake occurrence in form of earthquake belts representing boundaries of the plate.

The joining of the continental land masses of the globe into one large prehistoric unit has been attempted by several researchers in the early stage of the geosciences. Wegener provided several constraints for this hypothesis at the beginning of this century. But only extensive studies of the ocean bottom relief in the sixties gave the final insight into the sea-floor spreading and with this into the theory of the movement of a network of lithospheric blocks termed plates. This theory is called ´Plate Tectonics´ which describes the relative motion of the plates on a global scale.
The principal features of plate tectonics are summarized in Fig. 3.1-1.

The boundaries of plates can take four forms:

1. Oceanic ridges mark plate boundaries where magma from the Earth`s mantle ispwellingbetween separating plates. This gives rise to new oceanic lithosphere. These tectonic processes are connected with the occurrence of earthquakes. Therefore the oceanic ridges are represented as narrow earthquake belts, e.g. in the mid of the Atlantic, around Antarctica, in the Indic and Southeast Pacific (Fig. 3.1-2).

2 Trenches mark converging plate boundaries. Here oceanic lithosphere is thrusted generally beneath continental lithosphere. The process of underthrusting of oceanic lithosphere into the Earth´s mantle is called ´subduction´. The subduction zones are also marked by intensive earthquake activity. The precise localization of these earthquakes in space provides an excellent image of these subducting zones. The rate of subducting oceanic lithosphere is practically the same as the creation of new lithospheric material along the oceanic ridges. The circumpacific seismic belt (Fig. 3.1-2) represents high subduction zones where the creation of new oceanic lithosphere in the Pacific and in the Atlantic is compensated.

3. Transform faults are marked by tangential, usually parallel motion of two adjacent plates. Prominent features of major transform faults representing plate boundaries are the San Andreas fault in California and the North Anatolian fault which delineates the Anatolian microplate to the north and the Eurasian plate. Moreover, oceanic ridges are segmented by transform faults which can reach considerable extension (but these transform faults represent no plate boundaries).

4. Continent-continent collision occurs when the oceanic lithosphere between two continents has completely subducted - with the result that finally continental land masses converge whereby large mountain belts are created. This type of plate boundary stretches along the whole southern part of the Eurasian plate, i e from Gibraltar in the west up to Burma in the east The result of this continent-continent collision are the mountain belts, like the Atlas chains in Marocco, the Alps, Dinarides on the Balkan peninsula, the Zagros mountains in Iran, the Pamirs, Tienschan, and the Himalayas.

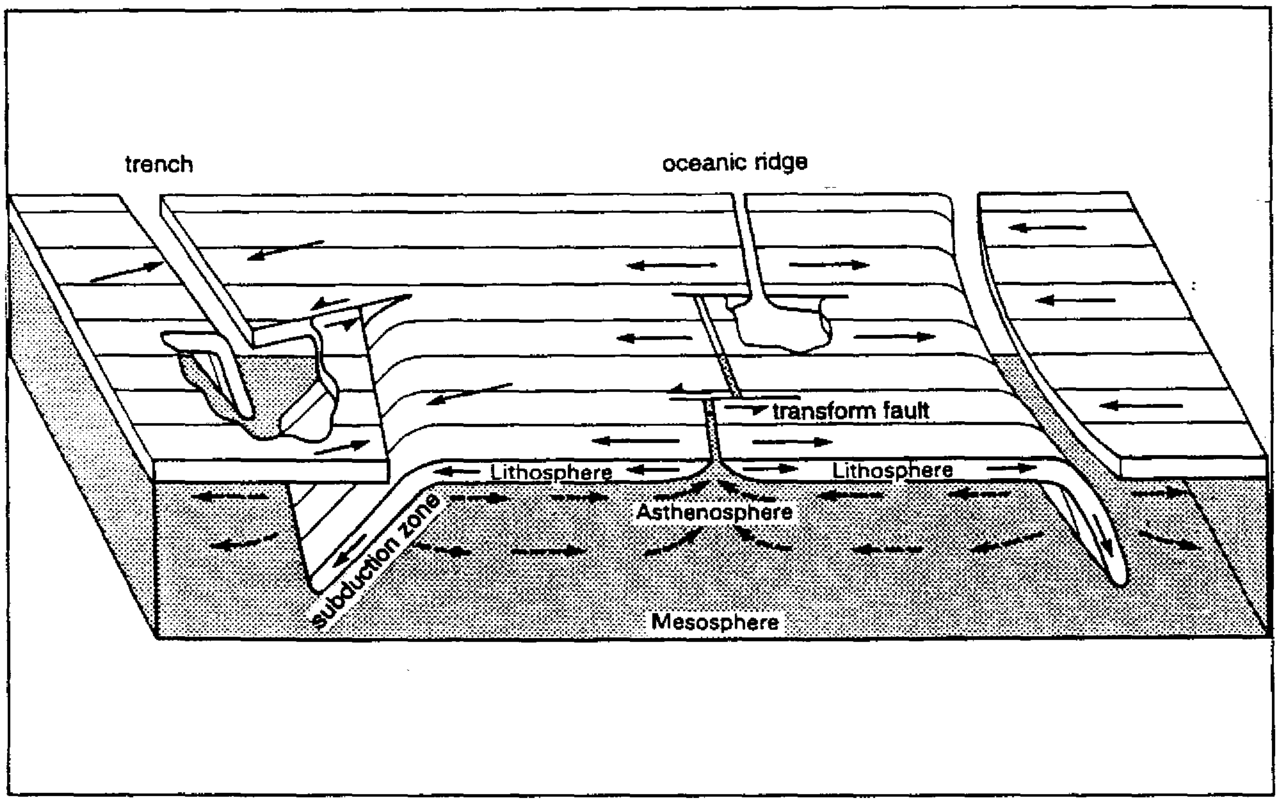


Figure 3.1-1 Scheme summarizing the principal features of plate tectonic processes (redrawn from Isacks et al. 1968)

Most of the world seismic activity is directly connected with the plate boundaries (Fig. 3.1-2). About 75% of the world seismic energy release is concentrated along the circumpacific belt, about 20% with the continent-continent collision from Gibraltar to the Far East; this zone is, from the seismological point of view, also called 'Mediterranean-central asiatic seismic belt'. A few percent of the world seismic activity is linked with the mid-oceanic ridges, while only a minor part of the earthquake activity occurs in weakness zones within plates itself.

Relative plate motions averaged over the past few million years, referred to as 'current' or 'present', are at quite well known locations and azimuths of transform faults and lineated magnetic anomalies, as well as slip vectors determined from analysis of earthquake focal mechanism, give information about the relative motion of adjacent plates. Data from all plate pairs can be combined to yield a self-consistent set of globally best fitting angular velocity vectors. These relative motions are interpreted as 'absolute' motions with the assumption of a reference frame, such as a hotspot assumed fixed relative to the mantle, or one in which there is 'no-net-rotation' of the set of motions (Fig. 3.1-3).

Plate tectonics show the origin of stresses in the lithosphere and especially in the Earth's crust where the most devastating earthquakes are located. Stresses are created due to sea-floor spreading along the ocean ridges due to the subduction process where pull forces exaggerate the subduction. The plates themselves react rather rigidly and are able to guide stresses extremely efficiently. The stress transmission through the plates causes only minor deformation of the plate interior. Locations of large deformations in the continents are the young mountain belts.

The driving forces for the plate tectonics are assumed to be large-scale convections in the Earth's mantle caused by lateral thermal differences of the viscous mantle material.Continents float in the form of thin hard plates on the mantle, which is elastic. The continents are readily deformed by changes in mass distribution over their surfaces, or by slight deformations of the mantle resulting from disturbances in its interior.

Furthermore, riding on the mantle convection, the land masses are considered to drift; the result of such drift isthe distribution of continents and islands as seen today.

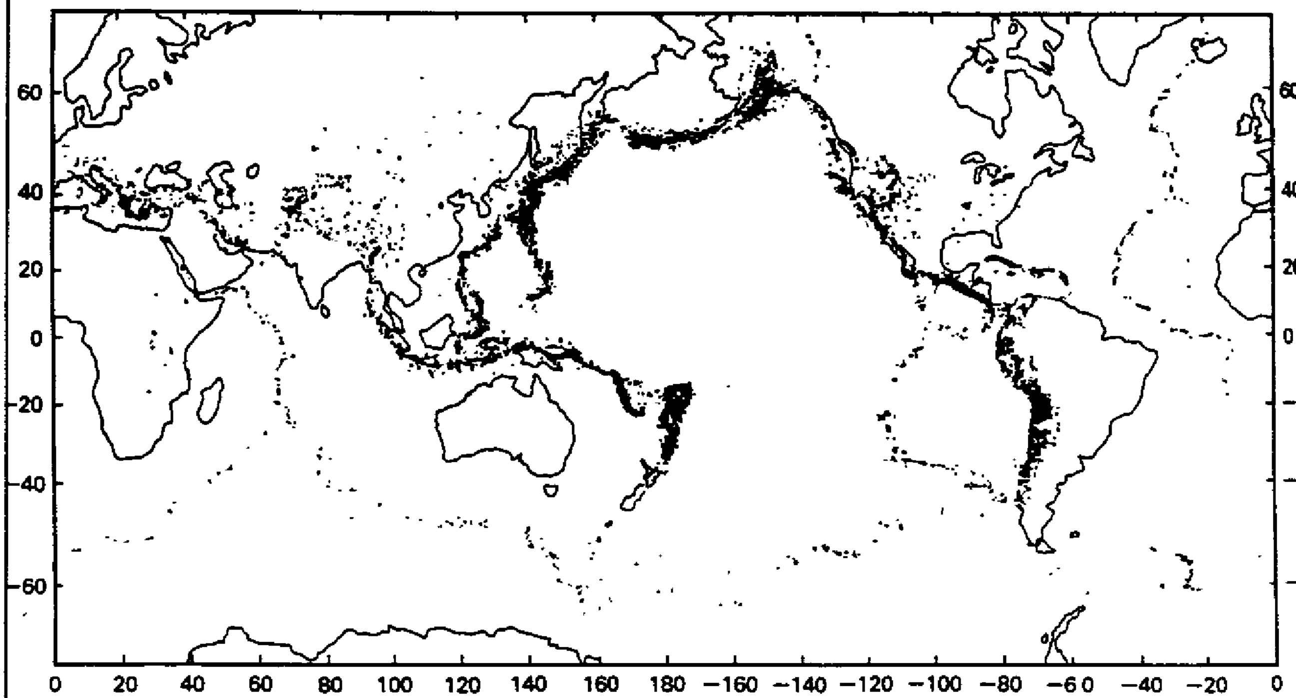


Figure 3.1-2 World seismicity (m_b > 4) for a seven years period (redrawn after Barazangi & Dormann, 1969). The seismic activity indicates like a radio beacon the active plate boundaries.

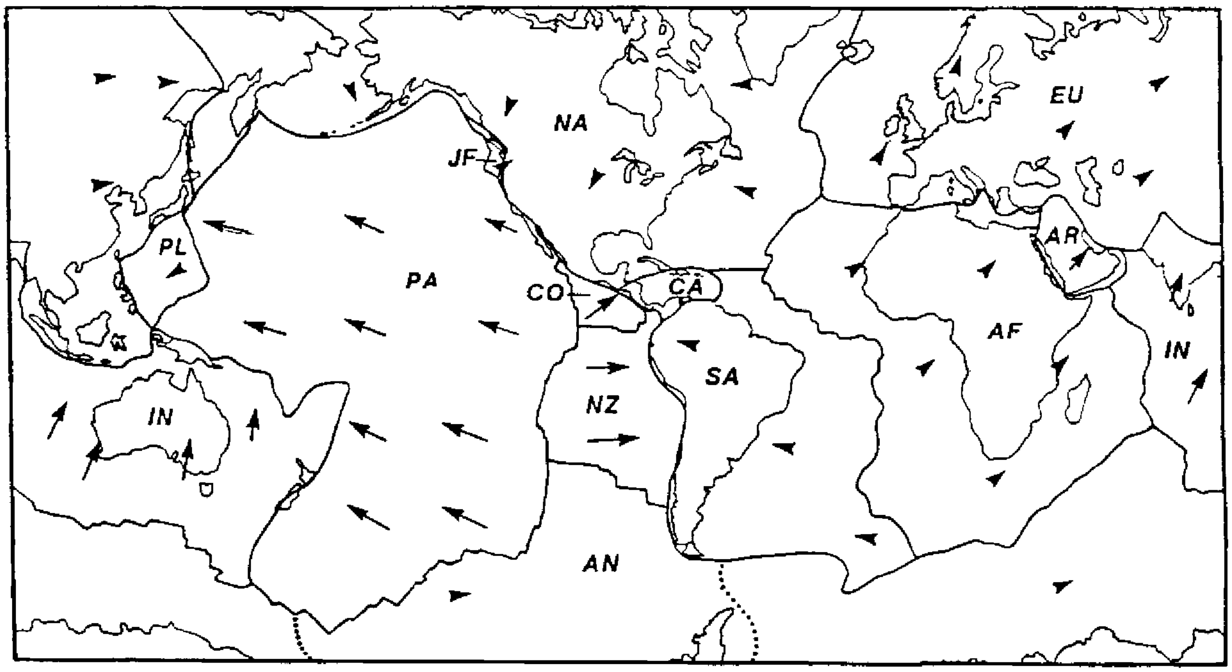


Figure 3.1-3 Present plate boundaries (from Gordon & Jurdy, 1986) and their motion related to minimal net-rotation of the set of motion. Plate codes: AF, African; AN, Antarctic; AR, Arabia; CA, Caribbean; CO, Cocos; EU, Eurasian; IN, Indian; NA, North American; NZ, Nazca; PA, Pacific; PL, Philippine; and SA, South American. Several so-called micro-plates are not shown.

plate tectonics, oceanic ridges, trenches, transform faults, plate motion.

SESSION 4: FAULTS

Topic 4.1 : Faults

Movements that take place along the faults are accompanied by ground shaking or earthquakes. The faults themselves remain as evidence of past events and can be studied for indication of the earthquakes they have caused and will cause.

A fault is a discontinuous surface across which shear displacement has occurred. The vector connecting a point to its original position before displacement is called the slip or displacement vector and its length defines the net slip. This can be resolved into a horizontal component parallel to the fault, the *strike-slip* component, and a vertical component parallel to the dip of the fault, the *dip-slip* component.

If faults cause earthquakes, what is then the cause of faulting? Faulting is the result of stress release due to movements within large plates that make up the Earth's crust which are in various stages of motion. The boundaries of these plates are the main zones of intense trembling with faulting and high seismic activity.

A fault itself is a shear rupture in the Earth along which opposite faces have been displaced relative to each other. Relative motion is parallel to the fault itself. Displacements may be from centimeters up to a few kilometers and may be in any direction. A rupture without relative displacement is termed Joint. The main types of faults are schematically illustrated in Fig. 4 1 (after Reiter, 1990).

Strike slip
Strike is the line of direction in a horizontal plane produced by intersection by a fault plane. Movement along this line is strike-slip. They need not to be vertical but are usually of high angle. The strike-slip faults can be right lateral or left lateral depending on the relative sense of motion.

Normal
A normal fault (Fig. 4.1) is one in which the *hanging wall* (the overlying side of the fault) has moved downward relative to the footwall (the underlying side of the fault).

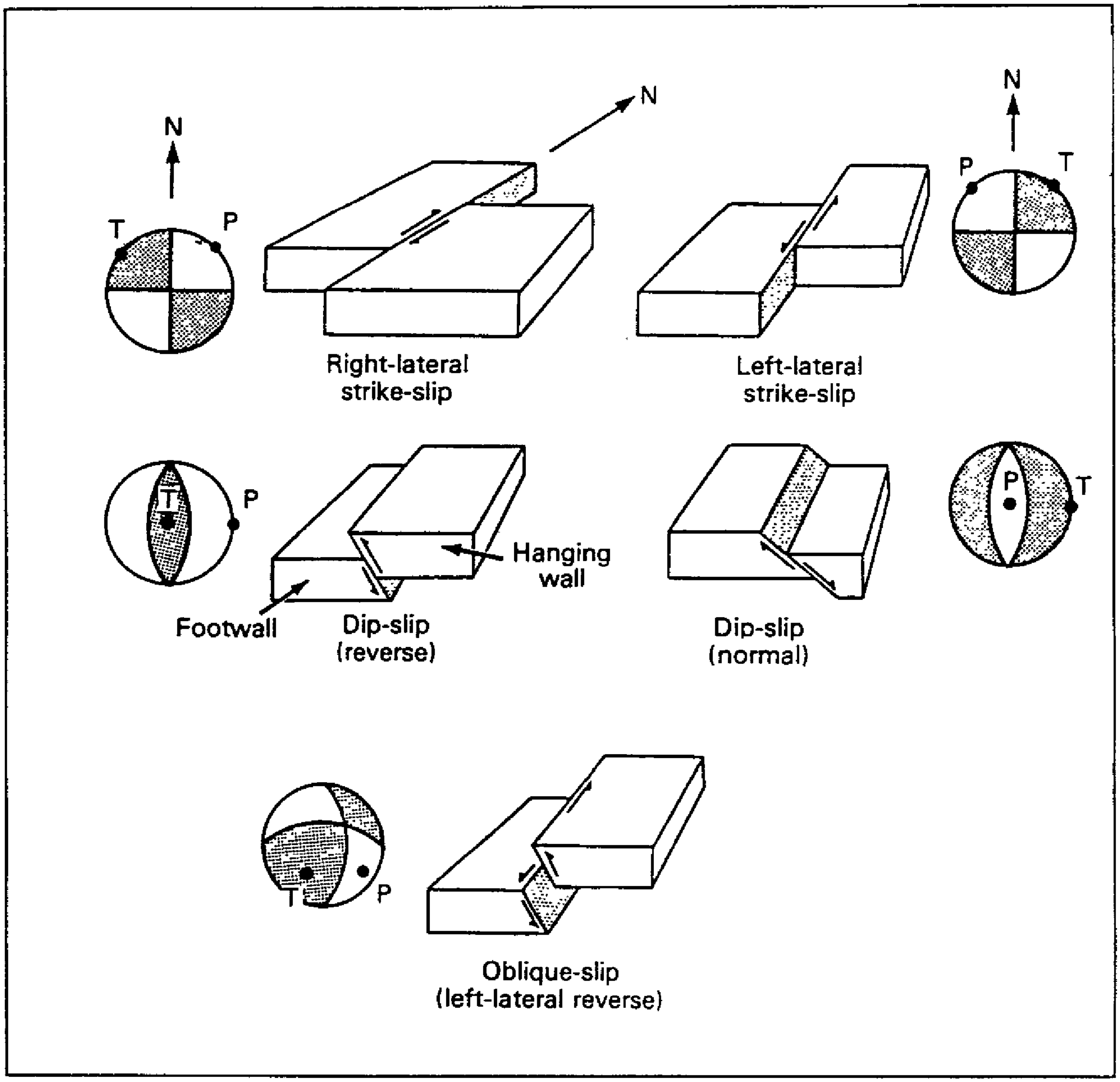


Figure 4.1-1 Different types of faults classified by the orientation of relative movement along the fault plane during an earthquake. Also shown are the corresponding focal mechanism solutions with pressure (P) and tension (T) axis (after Reiter, 1990).

Thrust or reverse
This is a fault (Fig. 4.1) in which the *hanging wall* has moved upward relative to the *footwall*. It is caused by dominating horizontal compression. Most faults are combinations of strike slip and one or the other of the above called oblique faulting. Also, the fault plane itself is likely to be curved. Blocks may be rotated relative to each other (Fig. 4.1). Fault displacements pinch out at the extremities.

Fig. 4.1 also shows the different earthquake focal mechanism solutions associated with the types of fault movements. P and T denote the direction of the axis of compression (P) and tension (T) in the underground.

The movements illustrated in Fig. 4.1 are highly simplified. In nature, they may be very complex with secondary and tertiary slippages related to primary fault movements.

? a. Give schematic illustrations of the main type of faults.
b. Explain the cause of faulting.

faults, dip-slip, compression axis, tension axis.

SESSION 5: EARTHQUAKES

Topic 5.1 : Description of earthquakes

Earthquakes represent the sudden release of accumulated stress by shear failure along a planar subsurface zone (fault plane). This causes vibrations (seismic waves) which are radiated into the surrounding rock and up to the surface. If enough energy is released in the earthquake, close to the source the waves may be large enough to be felt as a shaking of the ground. They may shake structures such as buildings, bridges, chimneys, etc., and even damage or destroy them. Both the cause (rock failure) and the effect (perceived ground shaking) are termed an earthquake. There are three types of actual earthquake: tectonic, volcanic, and man-made (induced due to human activities, i.e. mining, filling of reservoirs etc.).

The source of elastic energy, i.e., the focal region, is generally an extended volume of rock mass of irregular shape. The centroid of this volume is the focus. The center of the projection of rock mass on the Earth's surface is called the epicenter of the earthquake. Thus, the epicenter is a geographical point with a given latitude and longitude (Fig. 5.1-1; after Tiedemann 1993).

The distance of the epicenter from the place of observation or recording is called the epicentral distance. Since the distances involved on the Earth's surface are very large, it is a common practice to represent them in terms of angles measured, in degrees subtended by the two radii joining the epicenter and place of recording to the center of the Earth. One degree roughly corresponds to 110 km. The depth of focus varies from a few to as many as 700 km.

However, the geographical distribution of earthquakes with large focal depths is limited and the majority of those which cause destruction are restricted to focal depths of about 50 km. Earthquakes may be classified as those ones with shallow ($h \leq 70$ km), normal (70 - 300 km) and deep focus ($h > 300$ km).

Earthquakes caused by the collapse of large underground caves, large landslides, rock bursts in mines, meteoric impact, volcanic eruptions, etc. are in most cases insignificant.

The majority of earthquakes are caused by geologic structural changes in the Earth's crust and are called tectonic earthquakes. Volcanic earthquakes are caused by volcanic eruptions and are (with some exceptions) negligible.

The sketch of Fig. 5.1-1 illustrates the parameters to describe earthquakes:
The rupture begins at the hypocenter or focus, which is h kilometers below the epicenter on the ground surface. From the hypocenter, the rupture spreads at a velocity v, until it stops after involving an area of the length L and width W. The offset between the two sides of the fault may have some orientation in the fault plane. The angular deviation of the fault plane from north is the strike angle, the dip angle defines its inclination with respect to the horizontal ground surface. The distance from the element at risk is given with reference either to the epicenter or the hypocenter. In the first case the depth has to be considered, and it is evident that a relatively small strike angle would bring the energy release much closer to the risk shown in the illustration.

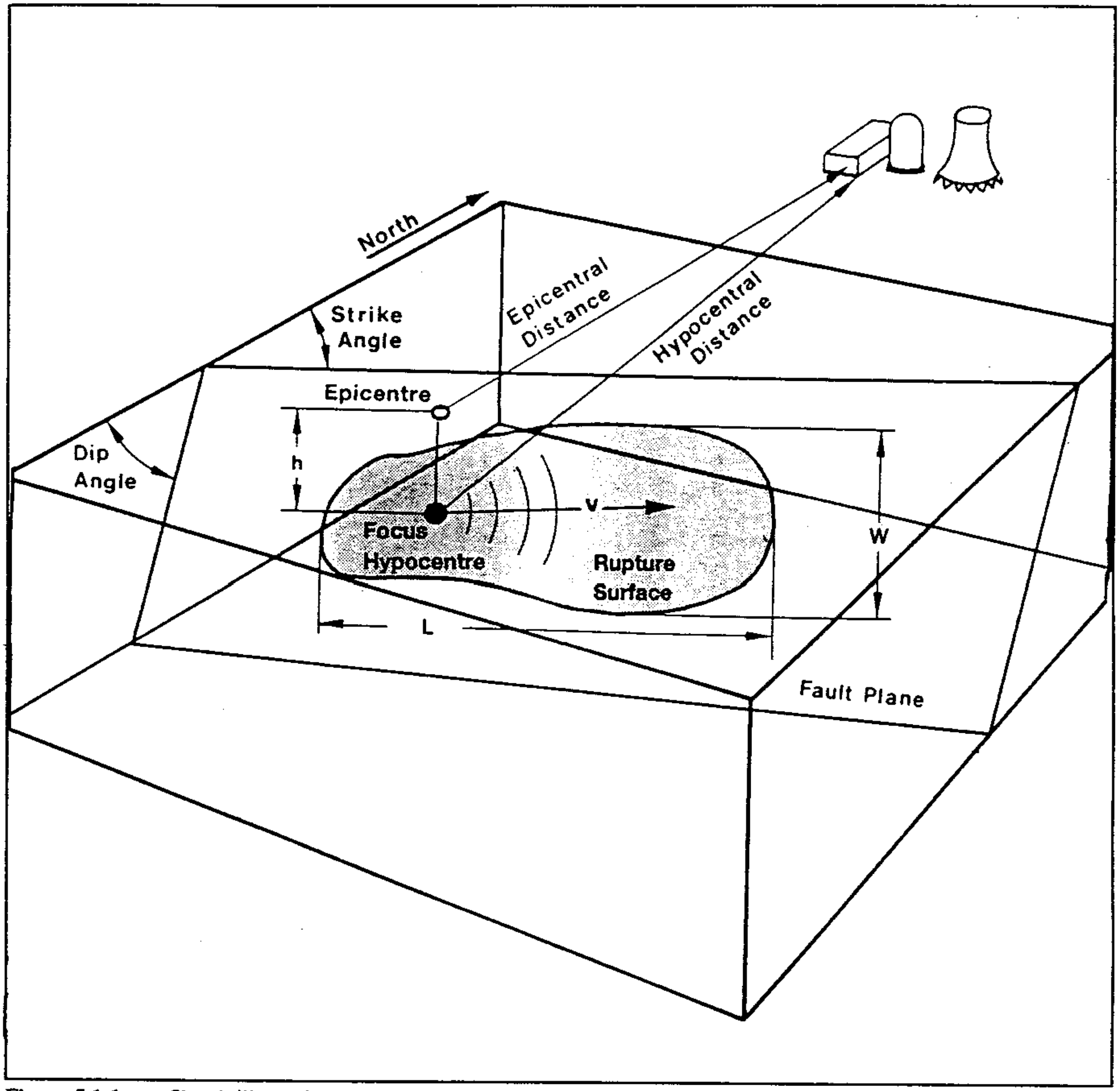


Figure 5.1-1 Sketch illustrating the parameters to describe an earthquake (after Tiedemann 1993)

earthquakes, epicentre, hypocentre, dip angle,
strike angle.

SESSION 6: EARTHQUAKE INTENSITY AND MAGNITUDE

Topic 6.1: Intensity and intensity assignment (macroseismic scales)

Because of the increasing importance of macroseismics and based on practice of intensity assignment using previous macroseismic scales and being aware of their shortcomings a highly innovative new scale has been developed by an international expert group. This new scale is in main parts an up-dated version of the MSK-64 scale. It has been introduced as the European Macroseismic Scale 1992; abraviated EMS-92 (ed. Grunthal 1993). The EMS-92 is in the meanwhile successfully used not only in Europe but in all other continents.

Definition of intensity:
The macroseismic intensity is a classification of the severity of ground shaking on the basis of observed effects in a limited area.
The investigation of earthquakes in terms of intensity is the matter of macroseismics. One can observe an increasing importance of macroseismics sinc the introduction of modern security philosophies against natural disasters which require reliable hazard assessments.
The Macroseismic method is the only one for the parametrization of historical, pre-instrumental earthquakes and for the as precise as possible description of the attenuation of potentially damaging soil motions with distance as an essential input-parameter for seismic hazard assessments.

Macroseismic investigations contain:
- The collection of observed and felt effects due to earthquakes, i.e. their intensity evaluation and depiction in form of macroseismic and/or isoseismal maps;
- The derivation of focal parameters of earthquakes, i.e. coordinates of epicentre, epicentral intenstynsity I_o, focal depth h and magnitude $M_m = f(I_o, h)$;
- The derivation of the intensity attenuation with distance, i.e. mean relations and local pecularities.

The intensity at a given location is determined by catalogueing observed effects. In the macroseismic study of an earthquake, the following simple stages can be discerned:

- Data acquisition - by questionnaires and field surveys, appeals for information, literature search (for historical events) and other means. (Standard form of questionnaires is distributed directly o individuals or displayed in newspapers with responses invited.)
- Data sorting - organisation of data into a form in which it can be interpreted by the user.
- Intensity assignment - interpretation of data using the descriptions of intensity scale.

This is usually then followed by mapping of intensities and by contouring to produce isoseismal maps. These maps are often the basis for establishing seismic zoning maps for engineering design purposes (earthquake resistant regulations/ codes).
The pattern of intensity generated by an earthquake is mainly determined by its energy release (magnitude), depth and focal mechanism (i.e. directio of rock movement). Local variations are caused by topography and

Differentiation of structures (buildings) into vulnerability classes:

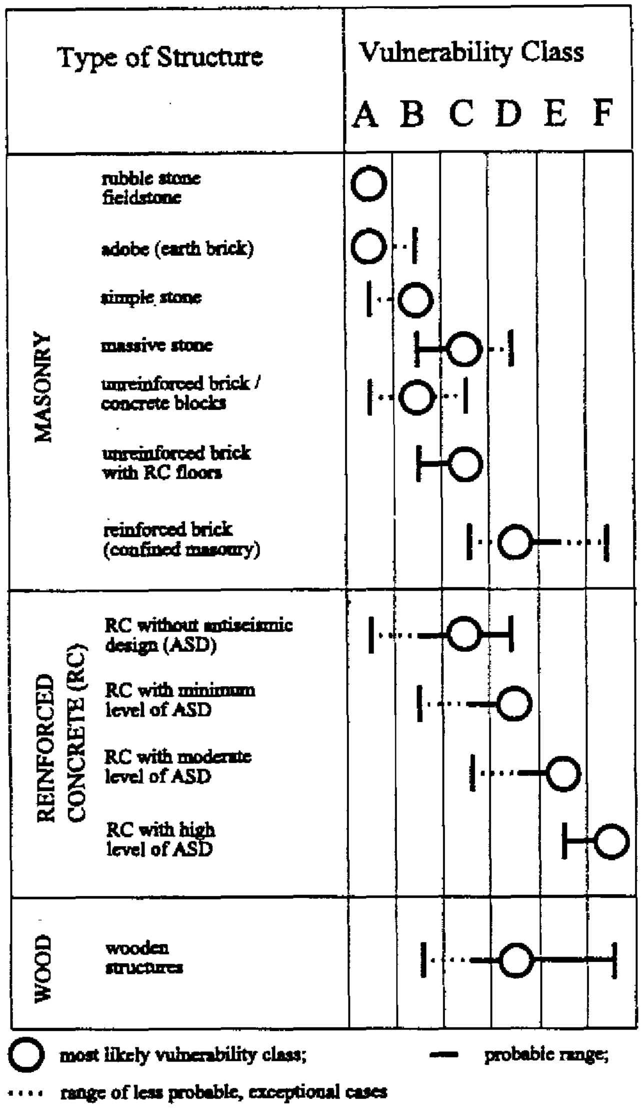
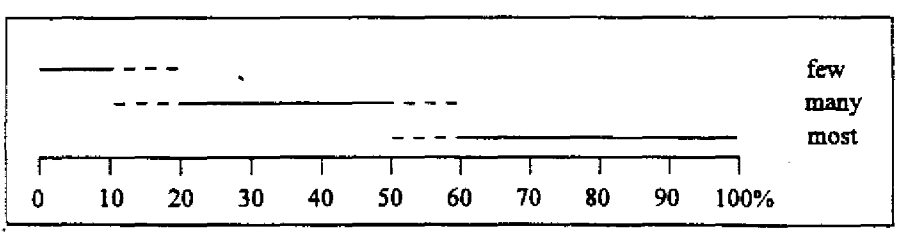


Table 6.1-1

Definition of quantity:



Classification of damage:

Table 6.1-2: Classification of damage to masonry buildings.

Note: the way in which a building deforms underearthquake loading depends on the building type. As a broad categorisation one can group together masonry buildings and buildings of reinforced concrete.

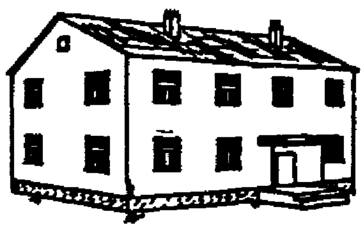
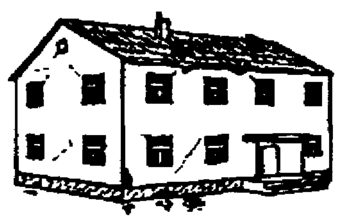
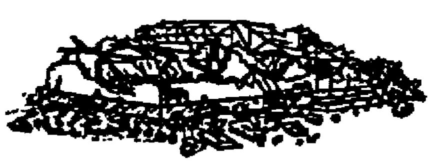
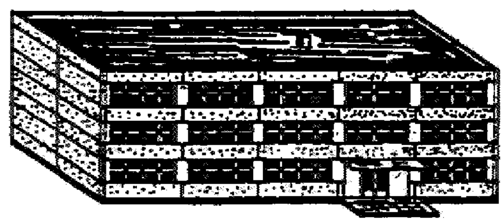
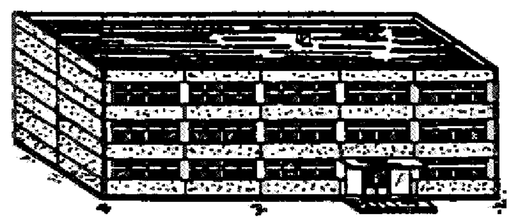
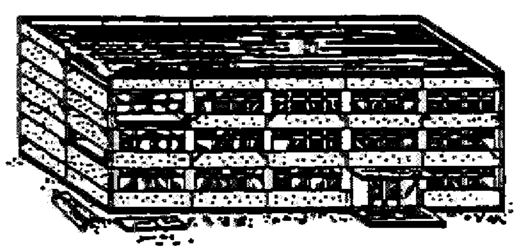
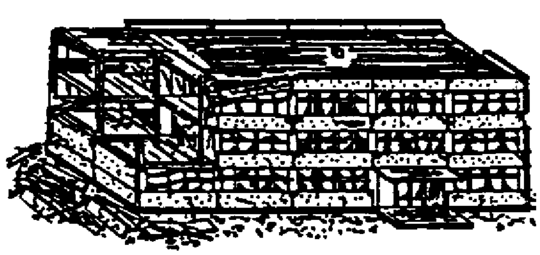
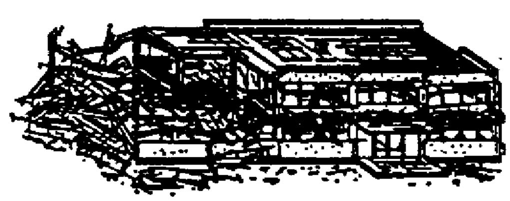
	Grade 1: **Negligible to slight damage (no structural damage)** hair-line cracks in very few walls; fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases only.
	Grade 2: **Moderate damage (slight structural damage, moderate non-structural damage)** cracks in many walls; fall of fairly large pieces of plaster; parts of chimneys fall down.
	Grade 3: **Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** large and extensive cracks in most walls; pantiles or slates slip off. Chimneys are broken at the roof line; failure of individual non-structural elements.
	Grade 4: **Very heavy damage (heavy structural damage, very heavy non-structural damage).** serious failure of walls; partial structural failure.
	Grade 5: **Destruction (very heavy structural damage)** total or near total collapse.

Table 6.1-3: Classification of damage to buildings of reinforced concrete.

	Grade 1: **Negligible to slight damage (no structural damage)** fine cracks in plaster over frame members and in partitions.
	Grade 2: **Moderate damage (slight structural damage, moderate non-structural damage)** hair-line cracks in in columns and beams; mortar falls from the joints of suspended wall panels; cracks in partition walls; fall of pieces of brittle cladding and plaster.
	Grade 3: **Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** cracks in columns with detachment of pieces of concrete, cracks in beams.
	Grade 4: **Very heavy damage (heavy structural damage, very heavy non-structural damage).** severe damage to the joints of the building skeleton with destruction of concrete and protusion of reinforcing rods; partial collapse; tilting of columns.
	Grade 5: **Destruction (very heavy structural damage)** total or near total collapse.