IITK - bmtpc
Earthquake Tip 1

Learning Earthquake Design and Construction

What causes Earthquakes?

The Earth and its Interior

Long time ago, a large collection of material masses coalesced and formed the Earth. Large amount of heat was generated by this fusion, and slowly as the Earth cooled, the heavier and denser materials sank to the center and the lighter ones rose to the top. The differentiated Earth consists of the *Inner Core* (radius ~1290*km*), the *Outer Core* (thickness ~2200*km*), the *Mantle* (thickness ~2900*km*) and the *Crust* (thickness ~5 to 40*km*). Figure 1 shows these layers. The Inner Core is solid and consists of heavy metals (*e.g.*, nickel and iron), while the Crust consists of light materials (*e.g.*, basalts and granites). The Outer Core is liquid in form and the Mantle has the ability to flow. At the Core, the temperature is estimated to be ~2500°C, the pressure ~4 million *atmospheres* and density ~13.5 *gm/cc*; this is in contrast to ~25°C, 1 *atmosphere* and 1.5 *gm/cc* on the surface of the Earth.

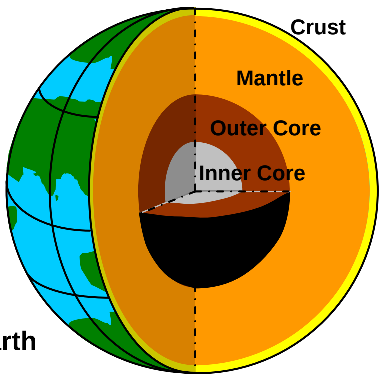

Figure 1:
Inside the Earth

The Circulations

Convection currents develop in the viscous Mantle, because of prevailing high temperature and pressure gradients between the Crust and the Core, like the convective flow of water when heated in a beaker (Figure 2). The energy for the above circulations is derived from the heat produced from the incessant decay of radioactive elements in the rocks throughout the Earth's interior. These convection currents result in a *circulation* of the earth's mass; hot molten lava comes out and the cold rock mass goes into the Earth. The mass absorbed eventually melts under high temperature and pressure and becomes a part of the Mantle, only to come out again from another location, someday. Many such local circulations are taking place at different regions underneath the Earth's surface, leading to different portions of the Earth undergoing different directions of movements along the surface.

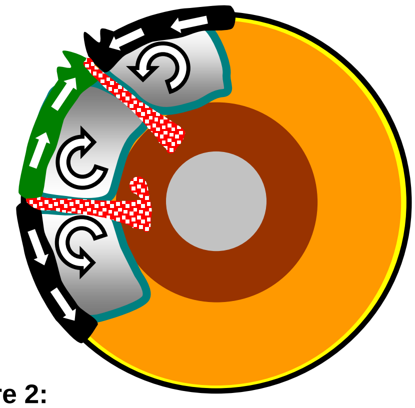

Figure 2:
Local Convective Currents in the Mantle

Plate Tectonics

The convective flows of Mantle material cause the Crust and some portion of the Mantle, to slide on the hot molten outer core. This sliding of Earth's mass takes place in pieces called *Tectonic Plates*. The surface of the Earth consists of seven major tectonic plates and many smaller ones (Figure 3). These plates move in different directions and at different speeds from those of the neighbouring ones. Sometimes, the plate in the front is slower; then, the plate behind it comes and collides (and *mountains* are formed). On the other hand, sometimes two plates move away from one another (and *rifts* are created). In another case, two plates move side-by-side, along the same direction or in opposite directions. These three types of inter-plate interactions are the *convergent*, *divergent* and *transform* boundaries (Figure 4), respectively. The convergent boundary has a peculiarity (like at the Himalayas) that sometimes neither of the colliding plates wants to sink. The relative movement of these plate boundaries varies across the Earth; on an average, it is of the order of a couple to tens of *centimeters per year*.

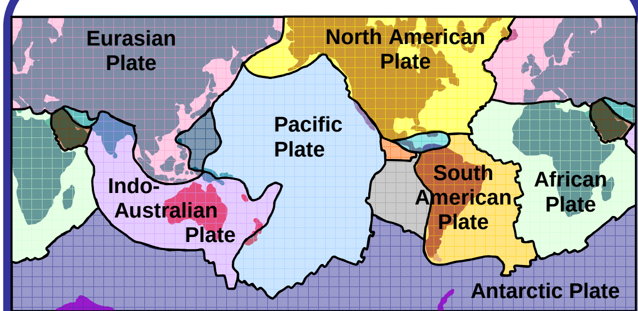

Figure 3:
Major Tectonic Plates on the Earth's surface

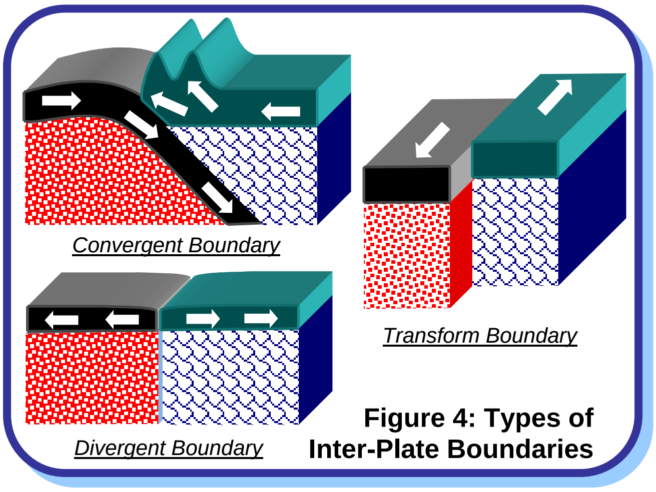

Figure 4: Types of Inter-Plate Boundaries

The Earthquake

Tectonic plates are made of elastic but brittle rocky material. And so, elastic strain energy is stored in them during the relative deformations that occur due to the gigantic tectonic plate actions taking place in the Earth. But, when the rocky material along the interface of the plates in the Earth's Crust reaches its strength, it fractures and a sudden movement takes place there (Figure 5); the interface between the plates where the movement has taken place (called the *fault*) suddenly *slips* and releases the large elastic strain energy stored in the rocks at the interface. For example, the energy released during the 2001 Bhuj (India) earthquake is about 400 times (or more) that released by the *1945 Atom Bomb* dropped on Hiroshima!!

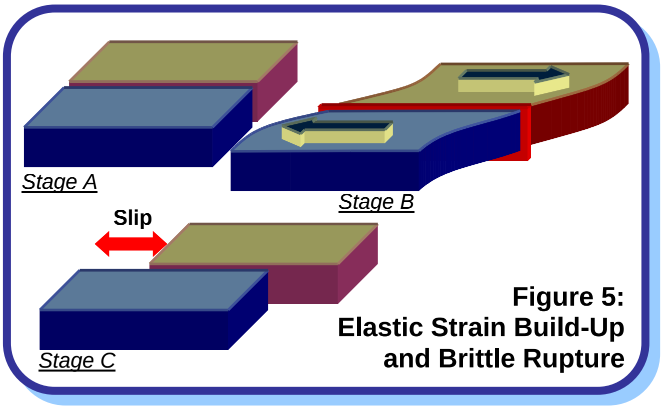

Figure 5: Elastic Strain Build-Up and Brittle Rupture

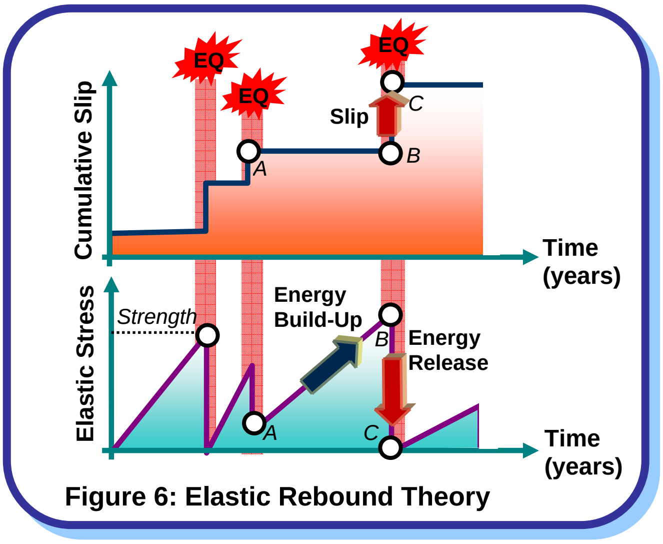

Figure 6: Elastic Rebound Theory

The sudden slip at the fault causes *the earthquake*… a violent shaking of the Earth during which large elastic strain energy released spreads out in the form of seismic waves that travel through the body and along the surface of the Earth. And, after the earthquake is over, the process of strain build-up at this modified interface between the tectonic plates starts all over again (Figure 6). Earth scientists know this as the *Elastic Rebound Theory*. The collection of material points at the fault over which slip occurs usually constitutes an oblong three-dimensional volume, with its long dimension often running into tens of kilometers in case of significant earthquakes.

Types of Earthquakes and Faults

Most earthquakes in the world occur along the boundaries of the tectonic plates as described above and are called *Inter-plate Earthquakes* (*e.g.*, 1897 Assam (India) earthquake). A number of earthquakes also occur within the plate itself but away from the plate boundaries (*e.g.*, 1993 Latur (India) earthquake); these are called *Intra-plate Earthquakes*. Here, a tectonic plate breaks in between. In both types of earthquakes, the slip generated at the fault during earthquakes is along both vertical and horizontal directions (called *Dip Slip*) and lateral directions (called *Strike Slip*) (Figure 7), with one of them dominating sometimes.

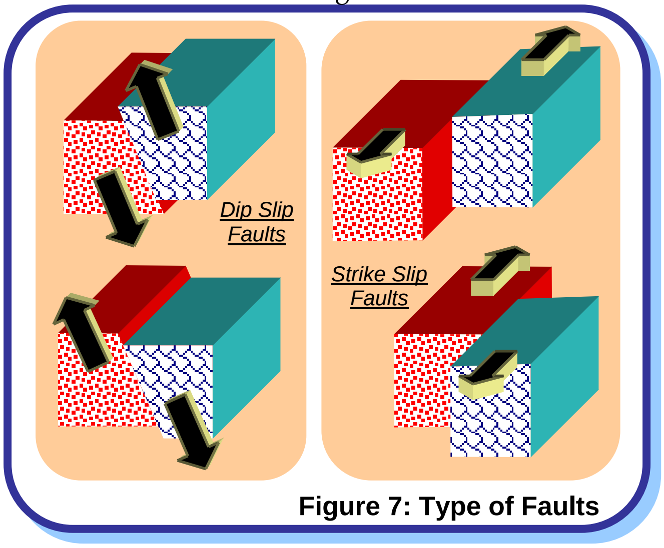

Figure 7: Type of Faults

Reading Material

Bolt,B.A., (1999), *Earthquakes*, Fourth Edition, W. H. Freeman and Company, New York, USA

http://earthquake.usgs.gov/faq/

http://neic.usgs.gov/neis/general/handouts/general_seismicity.html

http://www.fema.gov/kids/quake.htm

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How the ground shakes?

Seismic Waves

Large strain energy released during an earthquake travels as seismic waves in all directions through the Earth's layers, reflecting and refracting at each interface. These waves are of two types - *body waves* and *surface waves*; the latter are restricted to near the Earth's surface (Figure 1). Body waves consist of *Primary Waves (P-waves)* and *Secondary Waves (S-waves)*, and surface waves consist of *Love waves* and *Rayleigh waves*. Under P-waves, material particles undergo extensional and compressional strains along direction of energy transmission, but under S-waves, oscillate at right angles to it (Figure 2). Love waves cause surface motions similar to that by S-waves, but with no vertical component. Rayleigh wave makes a material particle oscillate in an elliptic path in the vertical plane (with horizontal motion along direction of energy transmission).

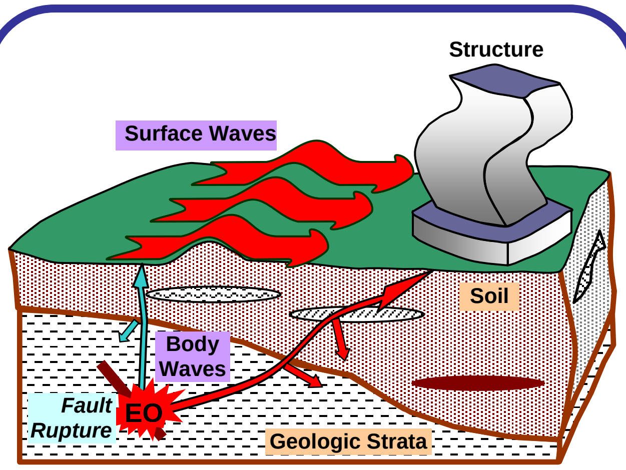

Figure 1: Arrival of Seismic Waves at a Site

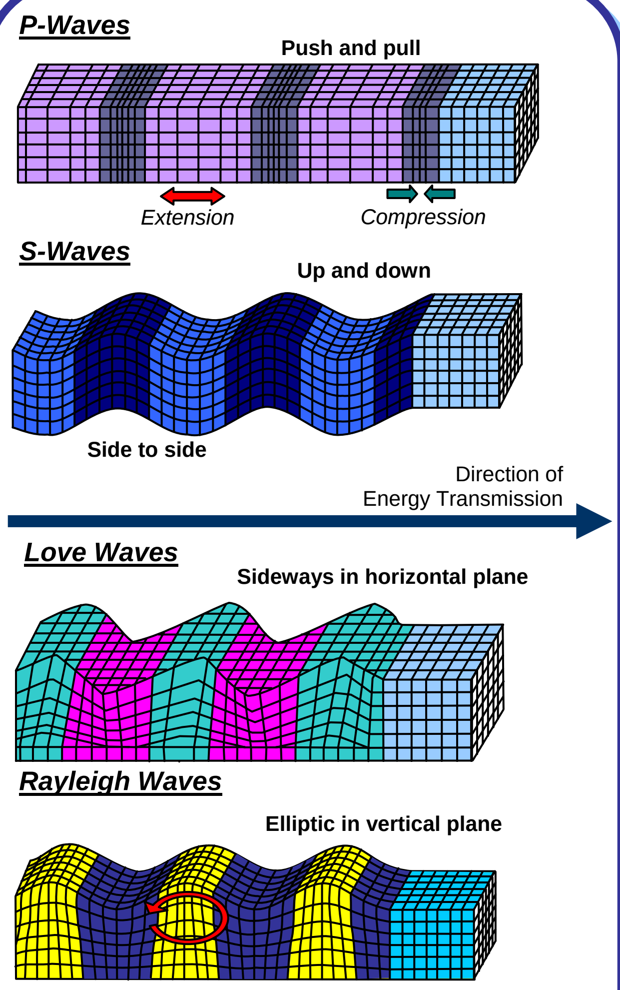

Figure 2: Motions caused by Body and Surface Waves (*Adapted from FEMA 99, Non-Technical Explanation of the NEHRP Recommended Provisions*)

P-waves are fastest, followed in sequence by S-, Love and Rayleigh waves. For example, in granites, P- and S-waves have speeds ~4.8 km/sec and ~3.0km/sec, respectively. S-waves do not travel through liquids. S-waves in association with effects of Love waves cause maximum damage to structures by their racking motion on the surface in both vertical and horizontal directions. When P- and S-waves reach the Earth's surface, most of their energy is reflected back. Some of this energy is returned back to the surface by reflections at different layers of soil and rock. Shaking is more severe (about twice as much) at the Earth's surface than at substantial depths. This is often the basis for designing structures buried underground for smaller levels of acceleration than those above the ground.

Measuring Instruments

The instrument that measures earthquake shaking, a *seismograph*, has three components – the *sensor*, the *recorder* and the *timer*. The principle on which it works is simple and is explicitly reflected in the early seismograph (Figure 3) – a pen attached at the tip of an oscillating simple pendulum (a mass hung by a string from a support) marks on a chart paper that is held on a drum rotating at a constant speed. A magnet around the string provides required damping to control the amplitude of oscillations. The pendulum mass, string, magnet and support together constitute the *sensor*; the drum, pen and chart paper constitute the *recorder*; and the motor that rotates the drum at constant speed forms the *timer*.

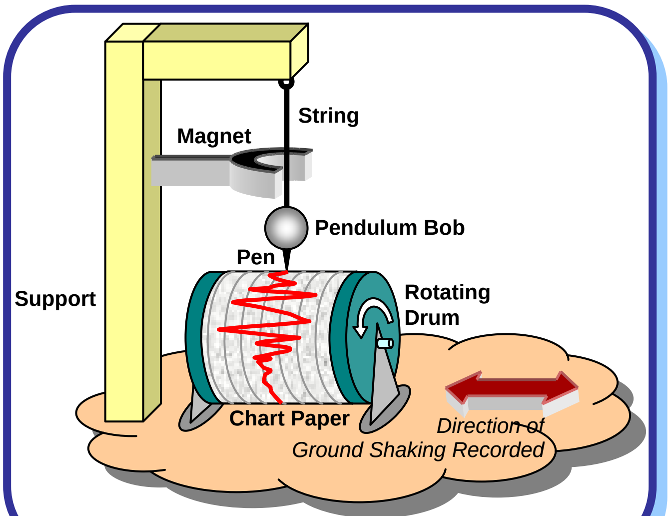

Figure 3: Schematic of *Early Seismograph*

One such instrument is required in each of the two orthogonal horizontal directions. Of course, for measuring vertical oscillations, the *string* pendulum (Figure 3) is replaced with a *spring* pendulum oscillating about a fulcrum. Some instruments do not have a timer device (*i.e.,* the drum holding the chart paper does not rotate). Such instruments provide only the maximum extent (or scope) of motion during the earthquake; for this reason they are called *seismoscopes*.

The analog instruments have evolved over time, but today, *digital instruments* using modern computer technology are more commonly used. The digital instrument records the ground motion on the memory of the microprocessor that is in-built in the instrument.

Strong Ground Motions

Shaking of ground on the Earth's surface is a net consequence of motions caused by seismic waves generated by energy release at each material point within the three-dimensional volume that ruptures at the fault. These waves arrive at various instants of time, have different amplitudes and carry different levels of energy. Thus, the motion at any site on ground is random in nature with its amplitude and direction varying randomly with time.

Large earthquakes at great distances can produce weak motions that may not damage structures or even be felt by humans. But, sensitive instruments can record these. This makes it possible to locate distant earthquakes. However, from engineering viewpoint, strong motions that can possibly damage structures are of interest. This can happen with earthquakes in the vicinity or even with large earthquakes at reasonable medium to large distances.

Characteristics of Strong Ground Motions

The motion of the ground can be described in terms of displacement, velocity or acceleration. The variation of ground acceleration with time recorded at a point on ground during an earthquake is called an *accelerogram*. The nature of accelerograms may vary (Figure 4) depending on energy released at source, type of slip at fault rupture, geology along the travel path from fault rupture to the Earth's surface, and local soil (Figure 1). They carry distinct information regarding ground shaking; *peak amplitude*, *duration of strong shaking*, *frequency content* (*e.g.,* amplitude of shaking associated with each frequency) and *energy content* (*i.e.,* energy carried by ground shaking at each frequency) are often used to distinguish them.

Peak amplitude (*peak ground acceleration, PGA*) is physically intuitive. For instance, a horizontal PGA value of *0.6g* (= *0.6* times the acceleration due to gravity) suggests that the movement of the ground can cause a maximum horizontal force on a rigid structure equal to *60%* of its weight. In a rigid structure, all points in it move with the ground by the same amount, and hence experience the same maximum acceleration of PGA. Horizontal PGA values greater than *1.0g* were recorded during the 1994 Northridge Earthquake in USA. Usually, strong ground motions carry significant energy associated with shaking of frequencies in the range *0.03-30Hz (i.e., cycles per sec)*.

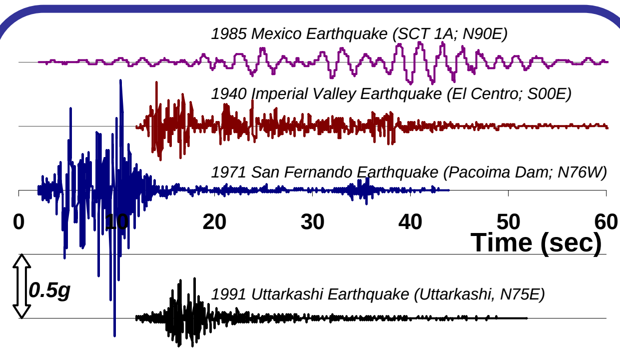

Figure 4:: Some typical recorded accelerograms

Generally, the maximum amplitudes of horizontal motions in the two orthogonal directions are about the same. However, the maximum amplitude in the vertical direction is usually less than that in the horizontal direction. In design codes, the vertical design acceleration is taken as $1/2$ to $2/3$ of the horizontal design acceleration. In contrast, the maximum horizontal and vertical ground accelerations *in the vicinity* of the fault rupture do not seem to have such a correlation.

Reading Material

Bolt,B.A., (1999), *Earthquakes*, Fourth Edition, W. H. Freeman and Company, New York, USA

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What are Magnitude and Intensity?

Terminology

The point on the fault where slip starts is the *Focus* or *Hypocenter*, and the point vertically above this on the surface of the Earth is the *Epicenter* (Figure 1). The depth of focus from the epicenter, called as *Focal Depth*, is an important parameter in determining the damaging potential of an earthquake. Most of the damaging earthquakes have shallow focus with focal depths less than about 70km. Distance from epicenter to any point of interest is called *epicentral distance*.

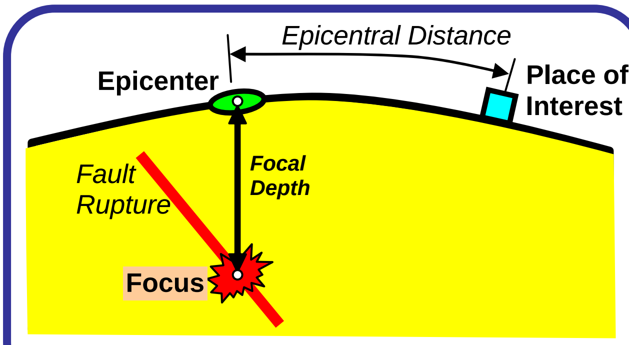

Figure 1: Basic terminology

A number of smaller size earthquakes take place before and after a big earthquake (*i.e.,* the *Main Shock*). Those occurring before the big one are called *Foreshocks*, and the ones after are called *Aftershocks*.

Magnitude

Magnitude is a *quantitative* measure of the actual size of the earthquake. Professor Charles Richter noticed that (a) at the same distance, seismograms (records of earthquake ground vibration) of larger earthquakes have bigger wave amplitude than those of smaller earthquakes; and (b) for a given earthquake, seismograms at farther distances have smaller wave amplitude than those at close distances. These prompted him to propose the now commonly used magnitude scale, the *Richter Scale*. It is obtained from the seismograms and accounts for the dependence of waveform amplitude on epicentral distance. This scale is also called *Local Magnitude* scale. There are other magnitude scales, like the *Body Wave Magnitude*, *Surface Wave Magnitude* and *Wave Energy Magnitude*. These *numerical* magnitude scales have no upper and lower limits; the magnitude of a very small earthquake can be zero or even negative.

An increase in magnitude (*M*) by 1.0 implies 10 times higher waveform amplitude and about 31 times higher energy released. For instance, energy released in a *M7.7* earthquake is about 31 times that released in a *M6.7* earthquake, and is about 1000 (≈31×31) times that released in a *M5.7* earthquake. Most of the energy released goes into heat and fracturing the rocks, and only a small fraction of it (fortunately) goes into the seismic waves that travel to large distances causing shaking of the ground en-route and hence damage to structures. (*Did you know?* The energy released by a *M6.3* earthquake is equivalent to that released by the 1945 Atom Bomb dropped on Hiroshima!!)

Earthquakes are often classified into different groups based on their size (Table 1). Annual average number of earthquakes across the Earth in each of these groups is also shown in the table; it indicates that on an average one *Great Earthquake* occurs each year.

Table 1: *Global occurrence of earthquakes*

Group	Magnitude	Annual Average Number
Great	8 and higher	1
Major	7 – 7.9	18
Strong	6 – 6.9	120
Moderate	5 – 5.9	800
Light	4 – 4.9	6,200 (estimated)
Minor	3 – 3.9	49,000 (estimated)
Very Minor	< 3.0	M2-3: ~1,000/day; M1-2: ~8,000/day

Source: http::/neic.usgs.gov/neis/eqlists/eqstats.html

Intensity

Intensity is a *qualitative* measure of the actual shaking at a location during an earthquake, and is assigned as *Roman Capital Numerals*. There are many intensity scales. Two commonly used ones are the *Modified Mercalli Intensity (MMI) Scale* and the *MSK Scale*. Both scales are quite similar and range from I (least perceptive) to XII (most severe). The intensity scales are based on three features of shaking – perception by people and animals, performance of buildings, and changes to natural surroundings. Table 2 gives the description of Intensity VIII on MSK Scale.

The distribution of intensity at different places during an earthquake is shown graphically using *isoseismals*, lines joining places with equal seismic intensity (Figure 2).

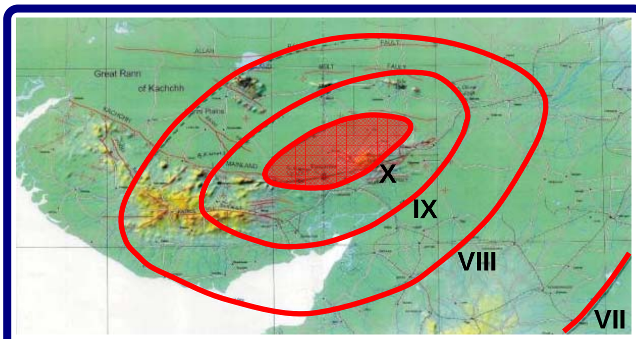

Figure 2: Isoseismal Map of the 2001 Bhuj (India) Earthquake (MSK Intensity)

Source:
http::/www.nicee.org/nicee/EQReports/Bhuj/isoseismal.html

Table 2: *Description of shaking intensity VIII as per MSK scale*

Intensity VIII - Destruction of Buildings

(a) Fright and panic. Also, persons driving motorcars are disturbed. Here and there branches of trees break off. Even heavy furniture moves and partly overturns. Hanging lamps are damaged in part.

(b) Most buildings of Type C suffer damage of Grade 2, and few of Grade 3. Most buildings of Type B suffer damage of Grade 3, and most buildings of Type A suffer damage of Grade 4. Occasional breaking of pipe seams occurs. Memorials and monuments move and twist. Tombstones overturn. Stonewalls collapse.

(c) Small landslips occur in hollows and on banked roads on steep slopes; cracks develop in ground up to widths of several centimeters. Water in lakes becomes turbid. New reservoirs come into existence. Dry wells refill and existing wells become dry. In many cases, changes in flow and level of water are observed.

Note:
- *Type A structures* - rural constructions; *Type B* - ordinary masonry constructions; *Type C* - Well-built structures
- *Single, Few* – about 5%; *Many* – about 50%; *Most* – about 75%
- *Grade 1 Damage* – Slight damage; *Grade 2* – Moderate damage; *Grade 3* – Heavy damage; *Grade 4* – Destruction; *Grade 5* – Total damage

Basic Difference: Magnitude *versus* Intensity

Magnitude of an earthquake is a measure of its size. For instance, one can measure the size of an earthquake by the amount of strain energy released by the fault rupture. This means that the magnitude of the earthquake is a *single* value for a given earthquake. On the other hand, *intensity* is an indicator of the severity of shaking generated at a given location. Clearly, the severity of shaking is much higher near the epicenter than farther away. Thus, during the same earthquake of a certain magnitude, different locations experience different levels of intensity.

To elaborate this distinction, consider the analogy of an electric bulb (Figure 3). The illumination at a location near a *100-Watt* bulb is higher than that farther away from it. While the bulb releases *100 Watts* of energy, the intensity of light (or illumination, measured in *lumens*) at a location depends on the wattage of the bulb and its distance from the bulb. Here, the size of the bulb (*100-Watt*) is like the magnitude of an earthquake, and the illumination at a location like the intensity of shaking at that location.

Magnitude and Intensity in Seismic Design

One often asks: *Can my building withstand a magnitude 7.0 earthquake?* But, the M7.0 earthquake causes different shaking intensities at different locations, and the damage induced in buildings at these locations is different. Thus, indeed it is particular levels of intensity of shaking that buildings and structures are designed to resist, and not so much the magnitude. The *peak ground acceleration* (*PGA*), *i.e.*, maximum acceleration experienced by the ground during shaking, is one way of quantifying the severity of the ground shaking. Approximate empirical correlations are available between the MM intensities and the PGA that may be experienced (*e.g.*, Table 3). For instance, during the 2001 Bhuj earthquake, the area enclosed by the isoseismal VIII (Figure 2) may have experienced a PGA of about *0.25-0.30g*. However, now strong ground motion records from seismic instruments are relied upon to quantify destructive ground shaking. These are critical for cost-effective earthquake-resistant design.

Table 3: *PGAs during shaking of different intensities*

MMI	V	VI	VII	VIII	IX	X
PGA (*g*)	0.03-0.04	0.06-0.07	0.10-0.15	0.25-0.30	0.50-0.55	>0.60

Source: B.A.Bolt, *Earthquakes*, W.H.Freeman and Co., New York, 1993

Based on data from past earthquakes, scientists Gutenberg and Richter in 1956 provided an approximate correlation between the Local Magnitude M_L of an earthquake with the intensity I_0 sustained in the epicentral area as: $M_L \approx \frac{2}{3} I_0 + 1$. (For using this equation, the Roman numbers of intensity are replaced with the corresponding Arabic numerals, *e.g.*, intensity IX with *9.0*). There are several different relations proposed by other scientists.

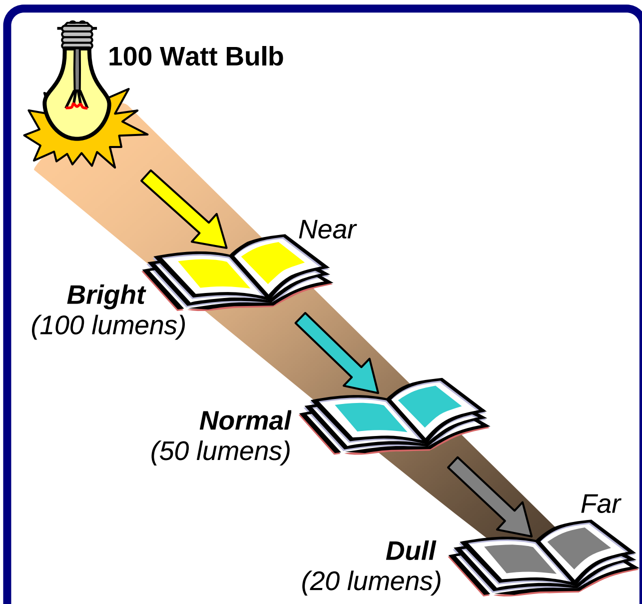

Figure 3: Reducing illumination with distance from an electric bulb

Reading Material

Richter,C.F., (1958), *Elementary Seismology*, W. H. Freeman and Company Inc, USA (Indian Reprint in 1969 by Eurasia Publishing House Private Limited, New Delhi)

http://neic.usgs.gov/neis/general/handouts/magnitude_intensity.html

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Where are the Seismic Zones in India?

Basic Geography and Tectonic Features

India lies at the northwestern end of the *Indo-Australian Plate*, which encompasses India, Australia, a major portion of the Indian Ocean and other smaller countries. This plate is colliding against the huge *Eurasian Plate* (Figure 1) and going under the Eurasian Plate; this process of one tectonic plate getting under another is called *subduction*. A sea, *Tethys*, separated these plates before they collided. Part of the lithosphere, the Earth's Crust, is covered by oceans and the rest by the continents. The former can undergo subduction at great depths when it converges against another plate, but the latter is buoyant and so tends to remain close to the surface. When continents converge, large amounts of shortening and thickening takes place, like at the Himalayas and the Tibet.

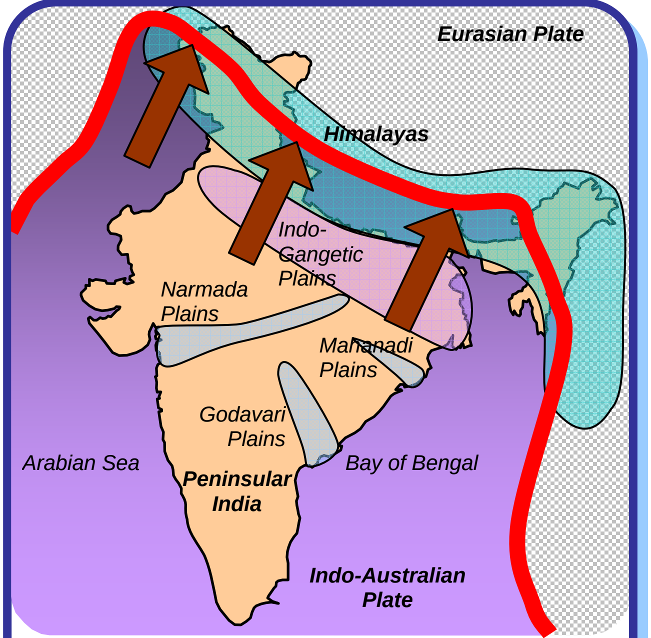

Figure 1: Geographical Layout and Tectonic Plate Boundaries at India

Three chief tectonic sub-regions of India are the mighty *Himalayas* along the north, the plains of the Ganges and other rivers, and the peninsula. The Himalayas consist primarily of sediments accumulated over long geological time in the Tethys. The Indo-Gangetic basin with deep alluvium is a great depression caused by the load of the Himalayas on the continent. The peninsular part of the country consists of ancient rocks deformed in the past Himalayan-like collisions. Erosion has exposed the roots of the old mountains and removed most of the topography. The rocks are very hard, but are softened by weathering near the surface. Before the Himalayan collision, several tens of millions of years ago, lava flowed across the central part of peninsular India leaving layers of basalt rock. Coastal areas like Kachchh show marine deposits testifying to submergence under the sea millions of years ago.

Prominent Past Earthquakes in India

A number of significant earthquakes occurred in and around India over the past century (Figure 2). Some of these occurred in populated and urbanized areas and hence caused great damage. Many went unnoticed, as they occurred deep under the Earth's surface or in relatively un-inhabited places. Some of the damaging and recent earthquakes are listed in Table 1. Most earthquakes occur along the Himalayan plate boundary (these are *inter-plate* earthquakes), but a number of earthquakes have also occurred in the peninsular region (these are *intra-plate* earthquakes).

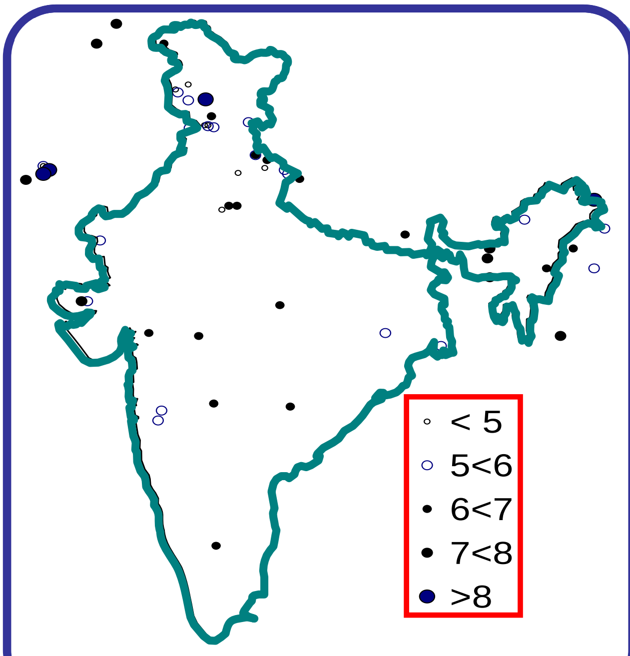

Figure 2: Some Past Earthquakes

Four Great earthquakes (M>8) occurred in a span of 53 years from 1897 to 1950; the January 2001 Bhuj earthquake (M7.7) is almost as large. Each of these caused disasters, but also allowed us to learn about earthquakes and to advance earthquake engineering. For instance, 1819 Cutch Earthquake produced an unprecedented *~3m* high uplift of the ground over *100km* (called *Allah Bund*). The 1897 Assam Earthquake caused severe damage up to *500km* radial distances; the type of damage sustained led to improvements in the intensity scale from I-X to I-XII. Extensive liquefaction of the ground took place over a length of *300km* (called the *Slump Belt*) during 1934 Bihar-Nepal earthquake in which many structures went afloat.

Table 1: Some Past Earthquakes in India

Date	Event	Time	Magnitude	Max. Intensity	Deaths
16 June 1819	Cutch	11:00	8.3	VIII	1,500
12 June 1897	Assam	17:11	8.7	XII	1,500
8 Feb. 1900	Coimbatore	03:11	6.0	X	Nil
4 Apr. 1905	Kangra	06:20	8.6	X	19,000
15 Jan. 1934	Bihar-Nepal	14:13	8.4	X	11,000
31 May 1935	Quetta	03:03	7.6	X	30,000
15 Aug. 1950	Assam	19:31	8.5	X	1,530
21 Jul. 1956	Anjar	21:02	7.0	IX	115
10 Dec. 1967	Koyna	04:30	6.5	VIII	200
23 Mar. 1970	Bharuch	20:56	5.4	VII	30
21 Aug. 1988	Bihar-Nepal	04:39	6.6	IX	1,004
20 Oct. 1991	Uttarkashi	02:53	6.6	IX	768
30 Sep. 1993	Killari (Latur)	03:53	6.4	IX	7,928
22 May 1997	Jabalpur	04:22	6.0	VIII	38
29 Mar. 1999	Chamoli	12:35	6.6	VIII	63
26 Jan. 2001	Bhuj	08:46	7.7	X	13,805
26 Dec. 2004	Sumatra	06:28	9.3	VII	10,749

The timing of the earthquake during the day and during the year critically determines the number of casualties. Casualties are expected to be high for earthquakes that strike during cold winter nights, when most of the population is indoors.

Seismic Zones of India

The varying geology at different locations in the country implies that the likelihood of damaging earthquakes taking place at different locations is different. Thus, a seismic zone map is required to identify these regions. Based on the levels of intensities sustained during damaging past earthquakes, the 1970 version of the zone map subdivided India into five zones – I, II, III, IV and V (Figure 3). The maximum Modified Mercalli (MM) intensity of seismic shaking expected in these zones were *V or less*, *VI*, *VII*, *VIII*, and *IX and higher*, respectively. Parts of Himalayan boundary in the north and northeast, and the Kachchh area in the west were classified as zone V.

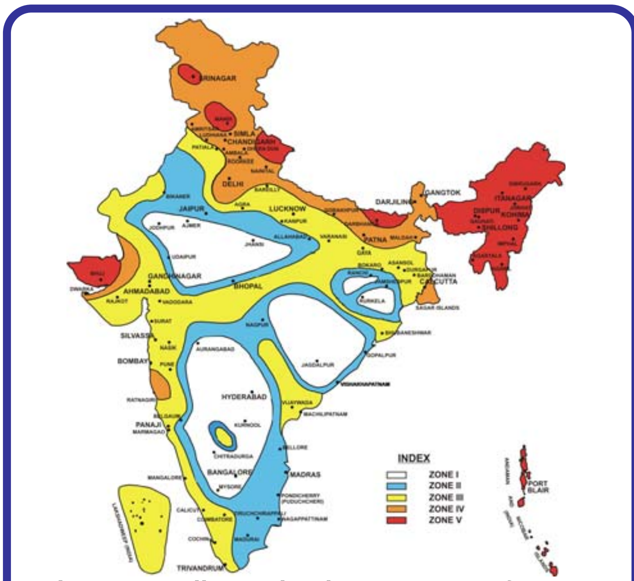

Figure 3: Indian Seismic Zone Map of 1970

The seismic zone maps are revised from time to time as more understanding is gained on the geology, the seismotectonics and the seismic activity in the country. The Indian Standards provided the first seismic zone map in 1962, which was later revised in 1967 and again in 1970. The map has been revised again in 2002 (Figure 4), and it now has only four seismic zones – II, III, IV and V. The areas falling in seismic zone I in the 1970 version of the map are merged with those of seismic zone II. Also, the seismic zone map in the peninsular region has been modified. Madras now comes in seismic zone III as against in zone II in the 1970 version of the map. This 2002 seismic zone map is not the final word on the seismic hazard of the country, and hence there can be no sense of complacency in this regard.

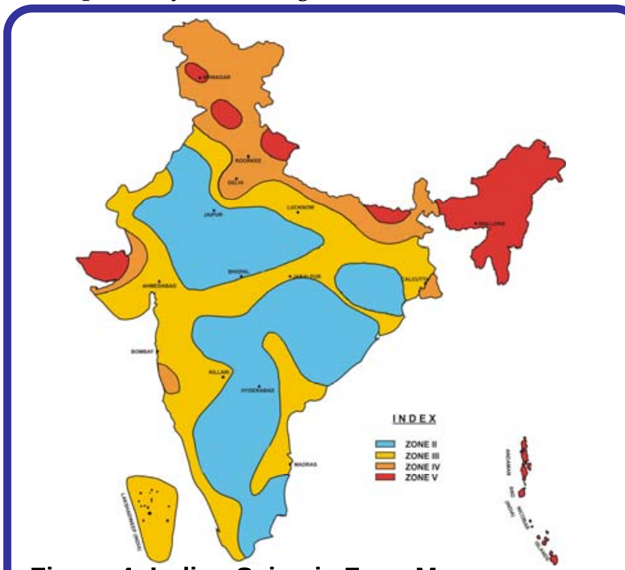

Figure 4: Indian Seismic Zone Map as per IS:1893 (Part 1)-2002

The national Seismic Zone Map presents a large-scale view of the seismic zones in the country. Local variations in soil type and geology cannot be represented at that scale. Therefore, for important projects, such as a major dam or a nuclear power plant, the seismic hazard is evaluated specifically for that site. Also, for the purposes of urban planning, metropolitan areas are microzoned. Seismic microzonation accounts for local variations in geology, local soil profile, *etc*,.

Reading Material

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