What Causes Earthquakes?

The Earth and its Interior

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.

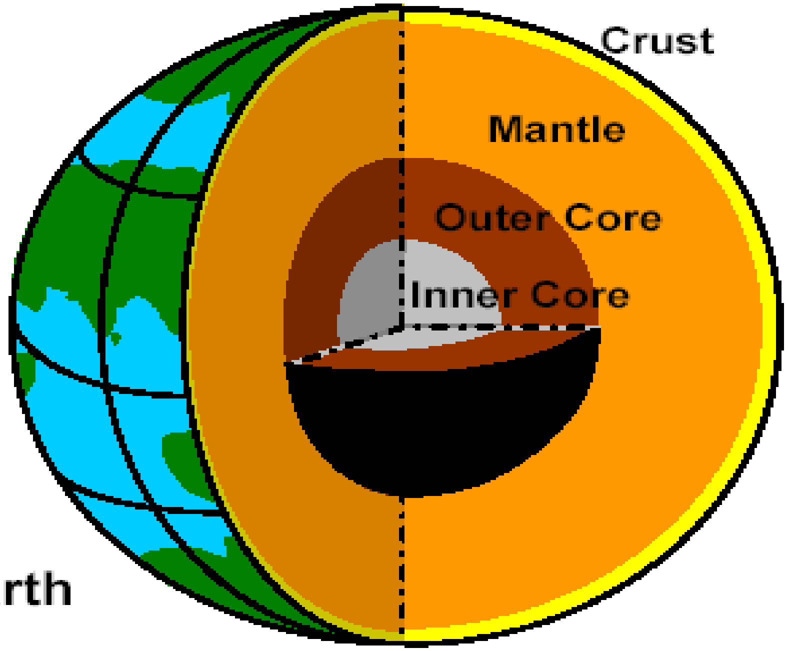

Figure 1:
Inside the Earth

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Lessons menu

- 1-What Causes Earthquakes
- 2-How the ground shakes
- 3-What are Magnitude and Intensity
- 4-Where are the Seismic Zones in India.
- 5-What are the Seismic Effects on Structures.
- 6-How Architectural Features Affect Buildings During Earthquakes.
- 7-How Buildings Twist During Earthquakes.
- 8-What is the Seismic Design Philosophy for Buildings.
- 9-How to Make Buildings Ductile for Good Seismic Performance.
- 10-How Flexibility of Buildings Affects their Earthquake Response.
- 11-What are the Indian Seismic Codes.
- 12-How do brick masonry houses behave during earthquakes.

- 13-Why should masonry buildings have simple structural configuration.
- 14-Why are horizontal bands necessary in masonry buildings.
- 15-Why is vertical reinforcement required in masonry buildings.
- 16-How to make Stone Masonry Buildings Earthquake Resistant.
- 17-how do earthquakes affect RC buildings.
- 18-how do beams in RC buildings resist earthquakes.
- 19-How do Columns in RC Buildings Resist Earthquakes.
- 20-How do Columns-Beams joints in RC Buildings Resist Earthquakes.
- 21-Why are Open-Ground Storey Buildings Vulnerable in Earthquakes.
- 22-Why are Short Columns more Damaged During Earthquakes.
- 23-Why are Buildings with Shear Walls Preferred in Seismic Regions.
- 24-How to Reduce Earthquake Effects on Buildings.

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.

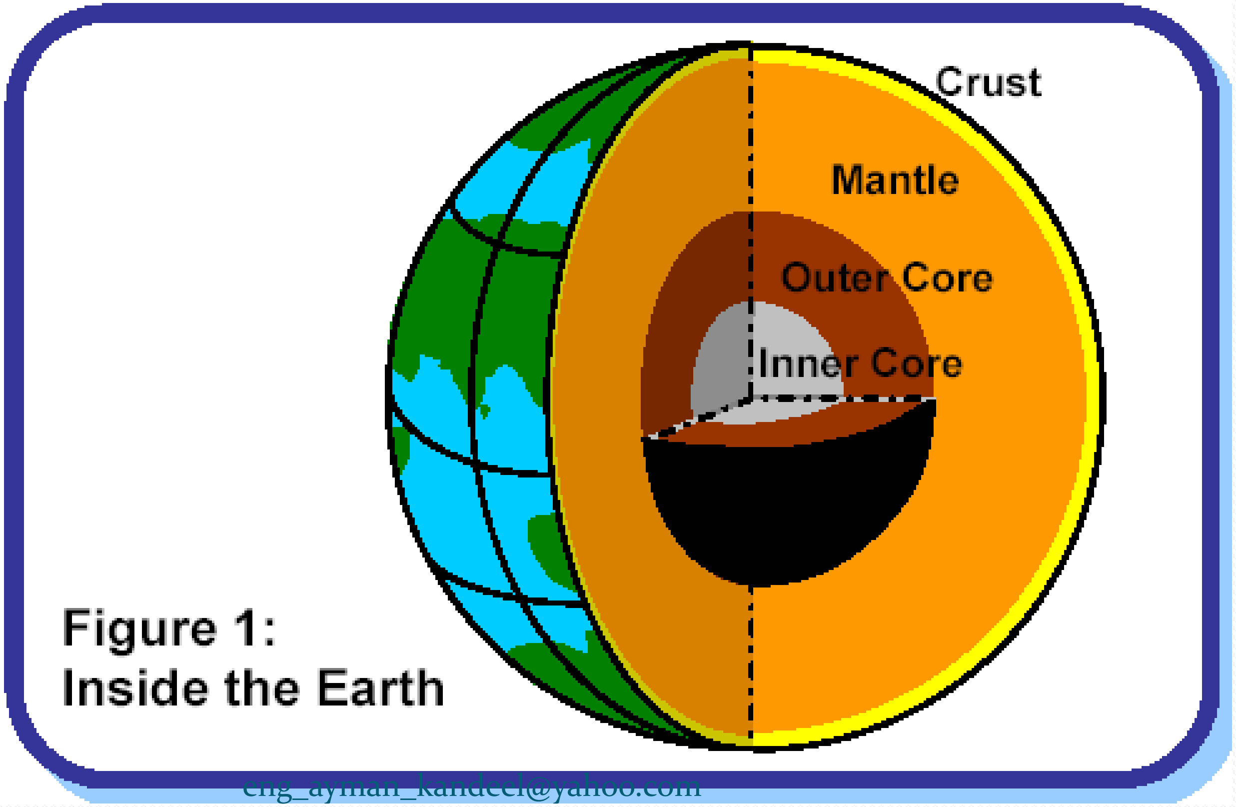

Figure 1:
Inside the Earth

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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

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,

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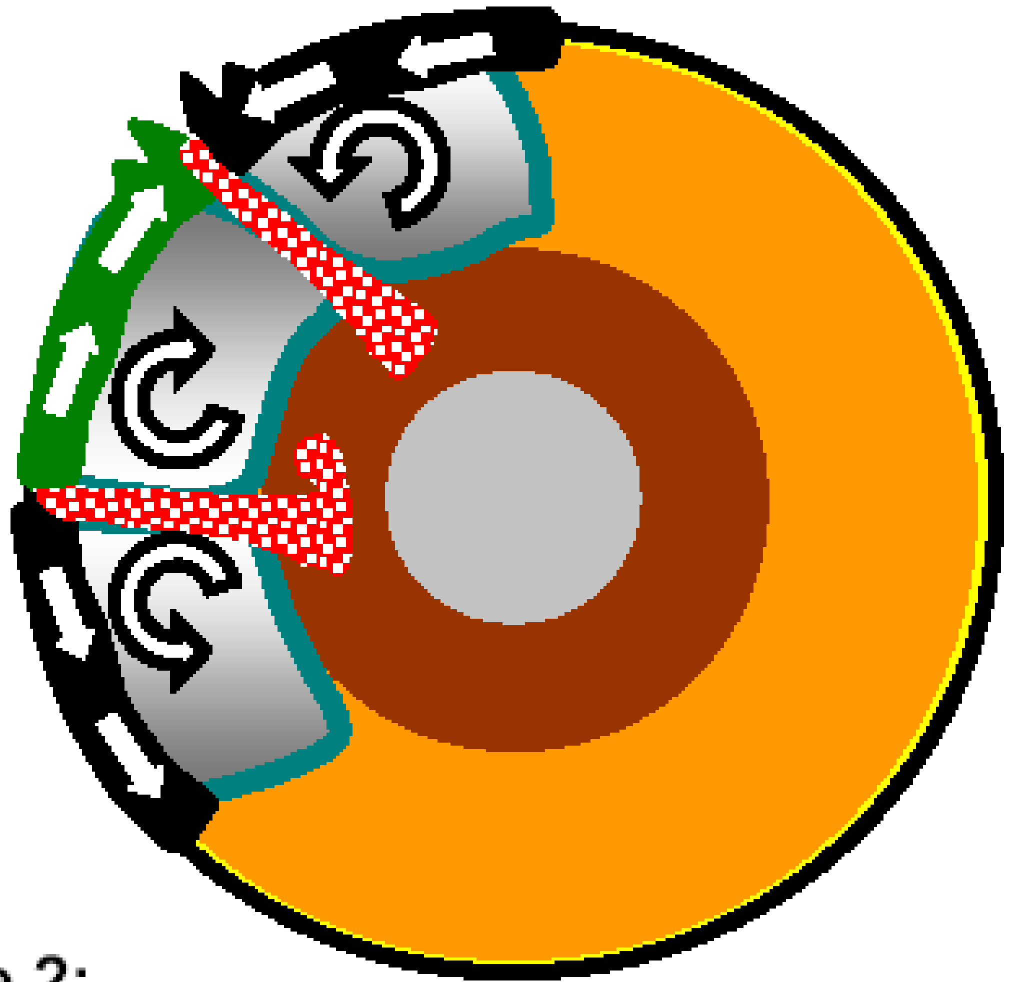

Figure 2:
Local Convective Currents in the Mantle

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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

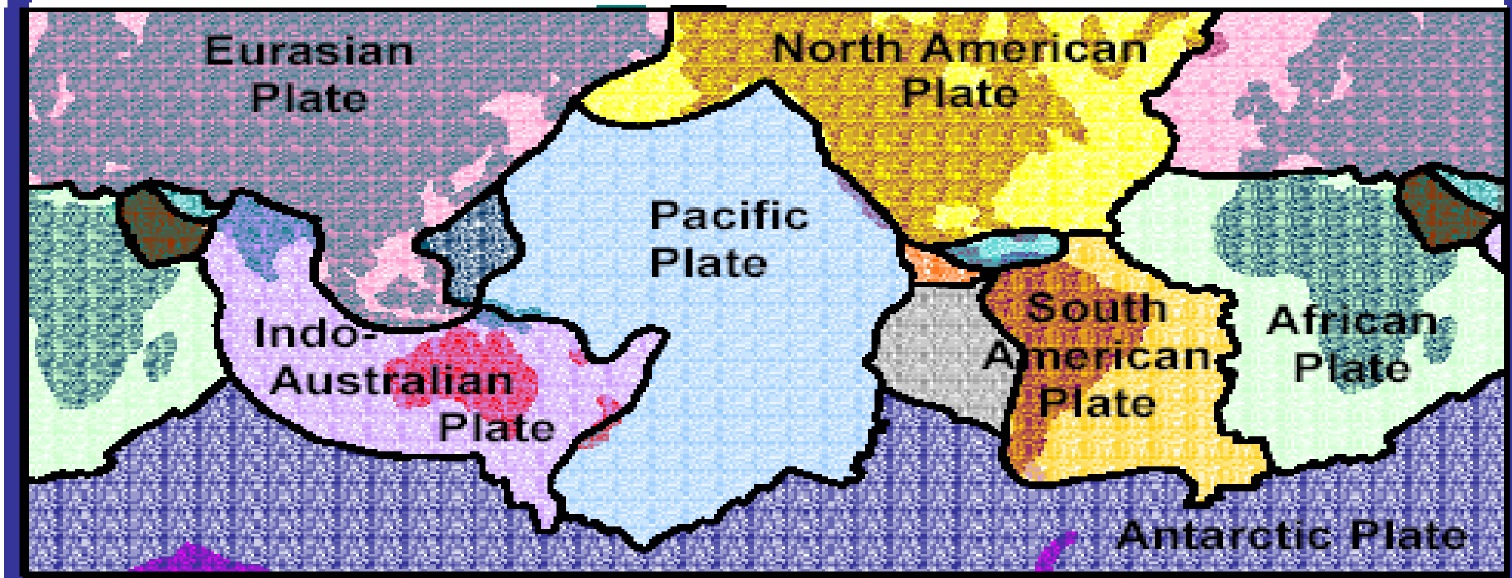

Figure 3:
Major Tectonic Plates on the Earth's surface

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What Causes Earthquakes?

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

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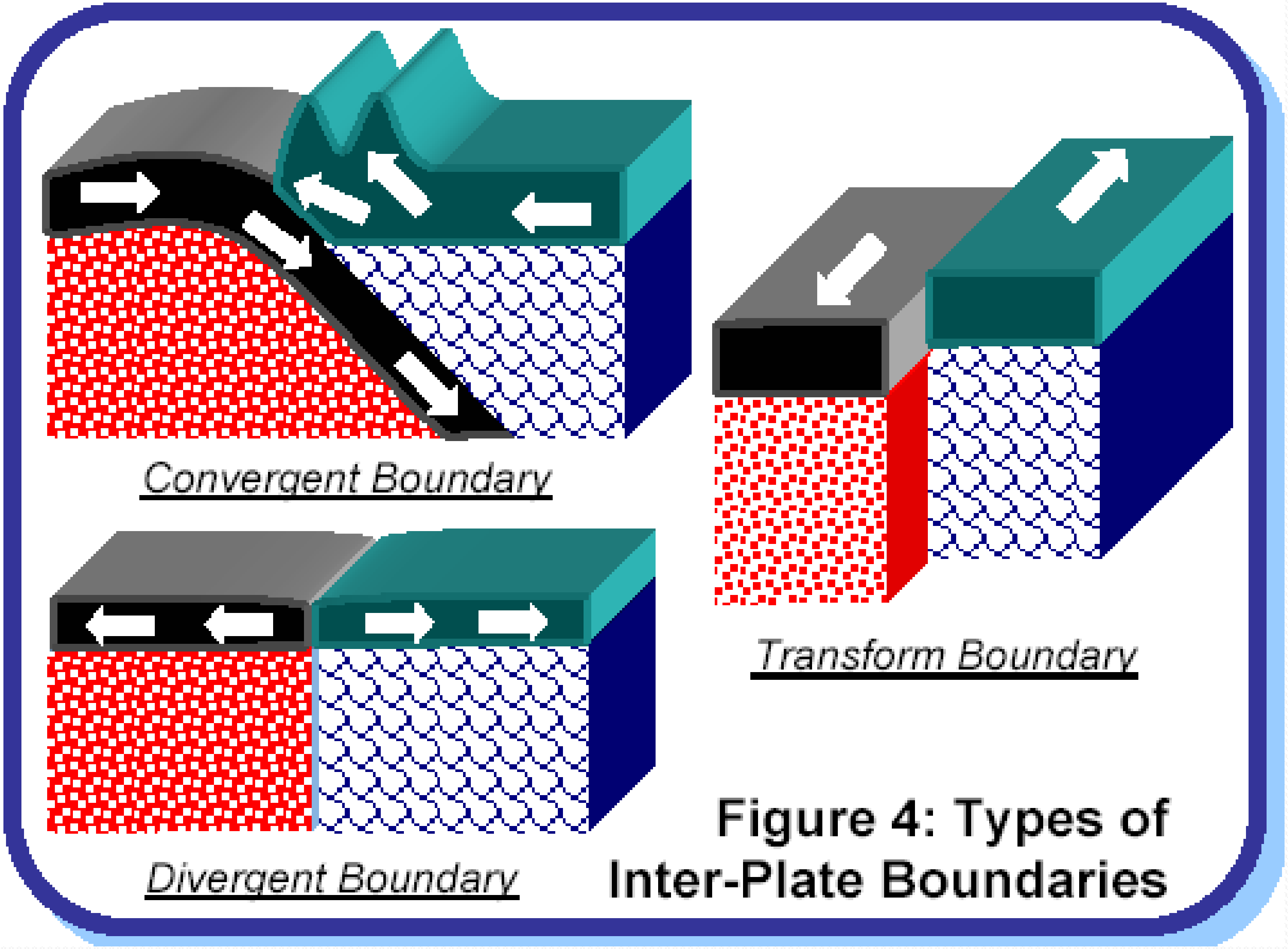

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The Earthquake

Rocks are made of elastic material, and so elastic strain energy is stored in them during the deformations that occur due to the gigantic tectonic plate actions that occur in the Earth. But, the material contained in rocks is also very brittle. Thus, when the rocks along a weak region in the Earth's Crust reach their strength, a sudden movement takes place there

(Figure 5); opposite sides of the *fault* (a crack in the rocks where movement has taken place) suddenly *slip* and release the large elastic strain energy stored in the interface rocks. 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!!

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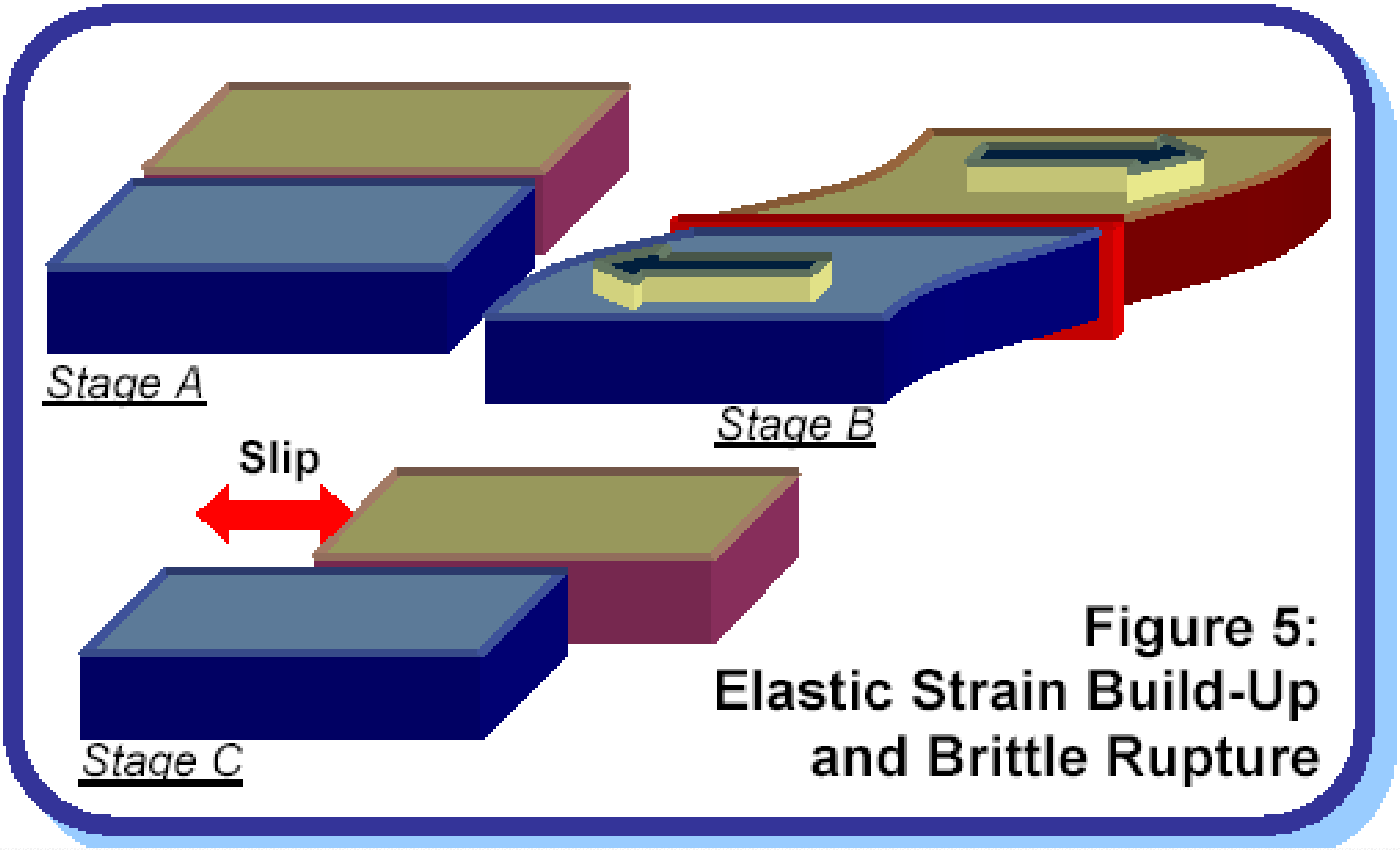

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The sudden slip at the fault causes *the earthquake*…. a violent shaking of the Earth when large elastic strain energy released spreads out through seismic waves that travel through the body and along the surface of the Earth. And, after the earthquake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

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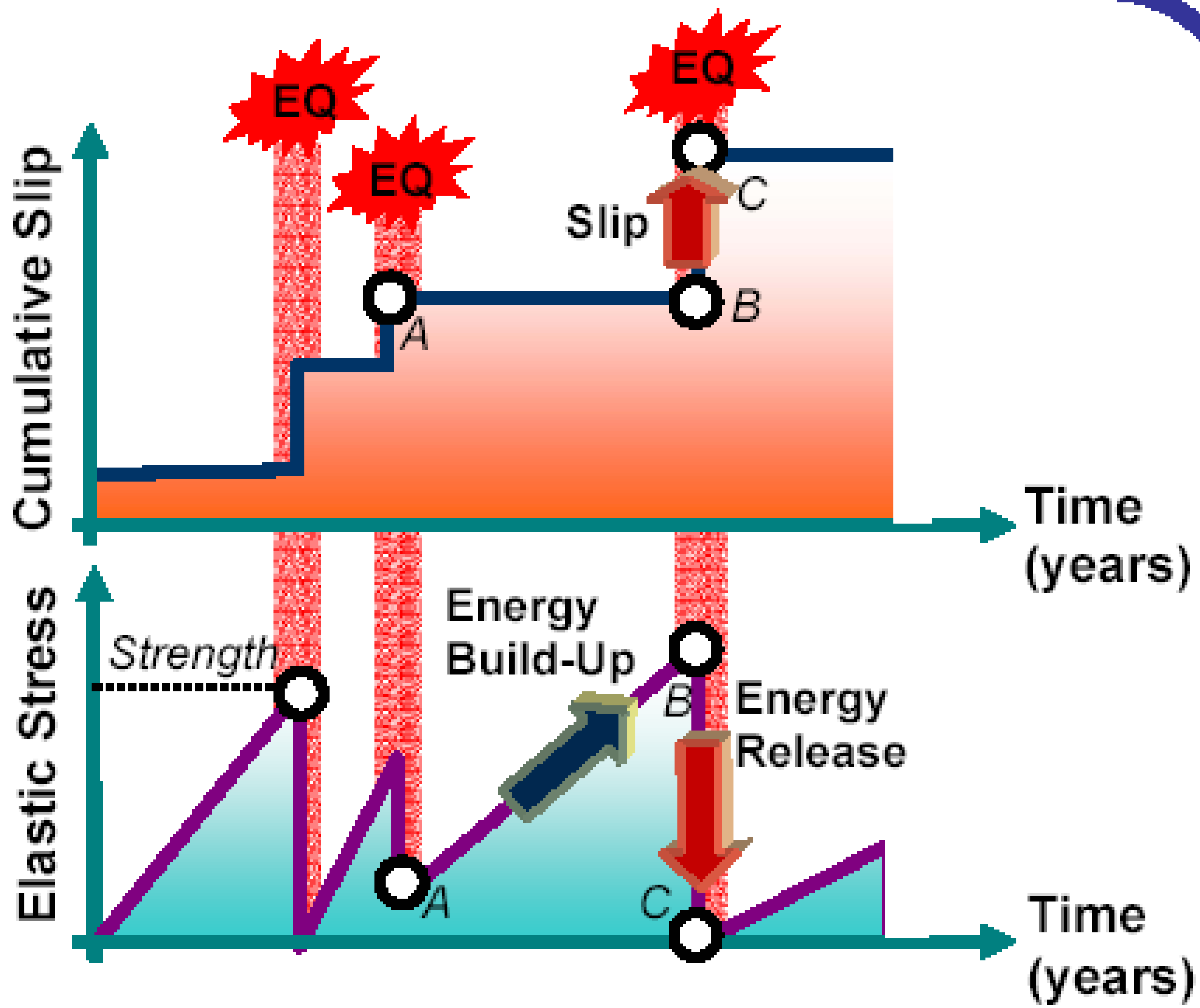

Figure 6: Elastic Rebound Theory

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Types of Earthquakes and Faults

Most earthquakes in the world occur along the boundaries of the tectonic plates and are called *Inter-plate Earthquakes* (*e.g.*, 1897 Assam (India) earthquake). A number of earthquakes also occur within the plate itself away from the plate boundaries (*e.g.*, 1993 Latur (India) earthquake); these are called *Intra-plate Earthquakes*. 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.

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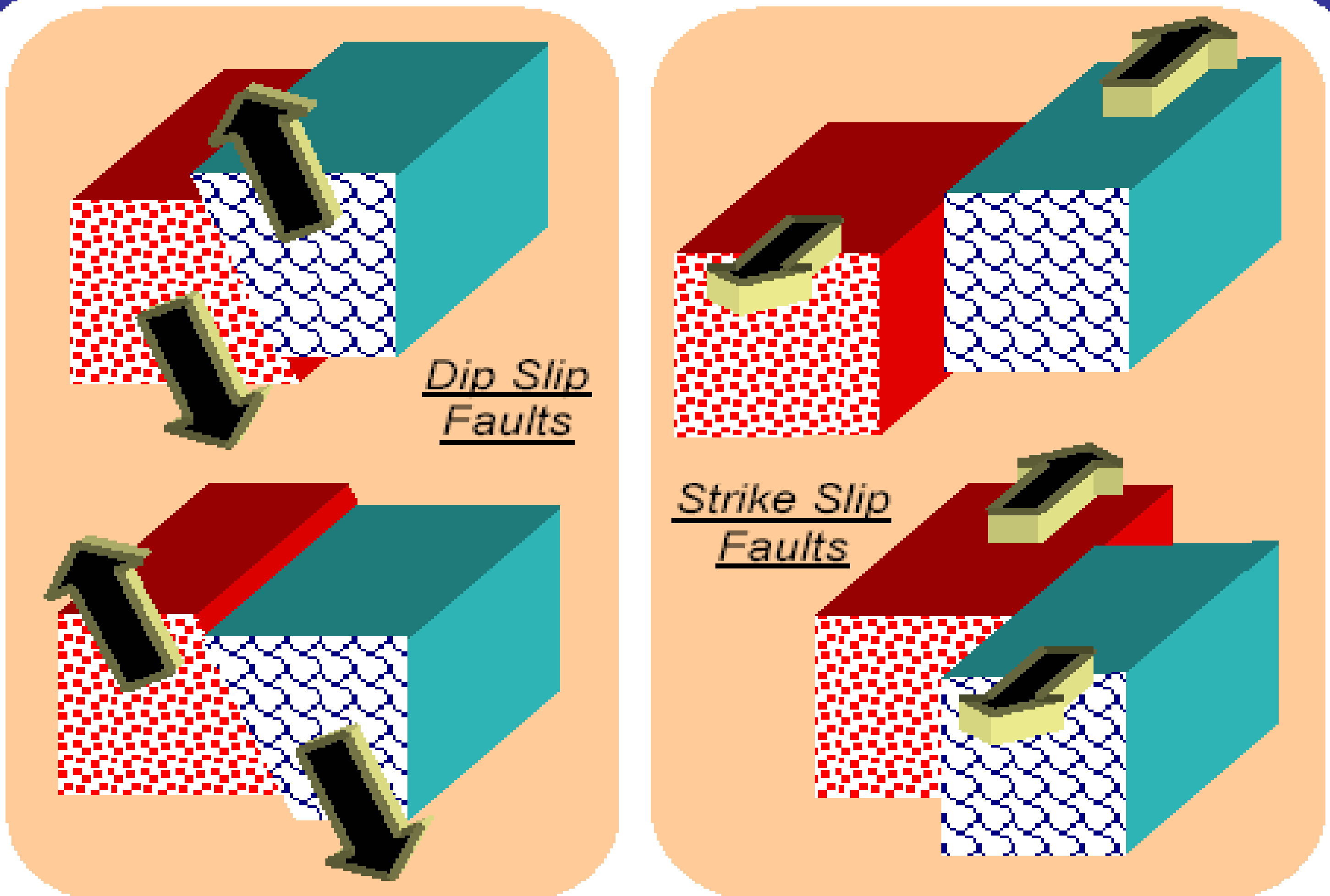

Figure 7: Type of Faults

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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

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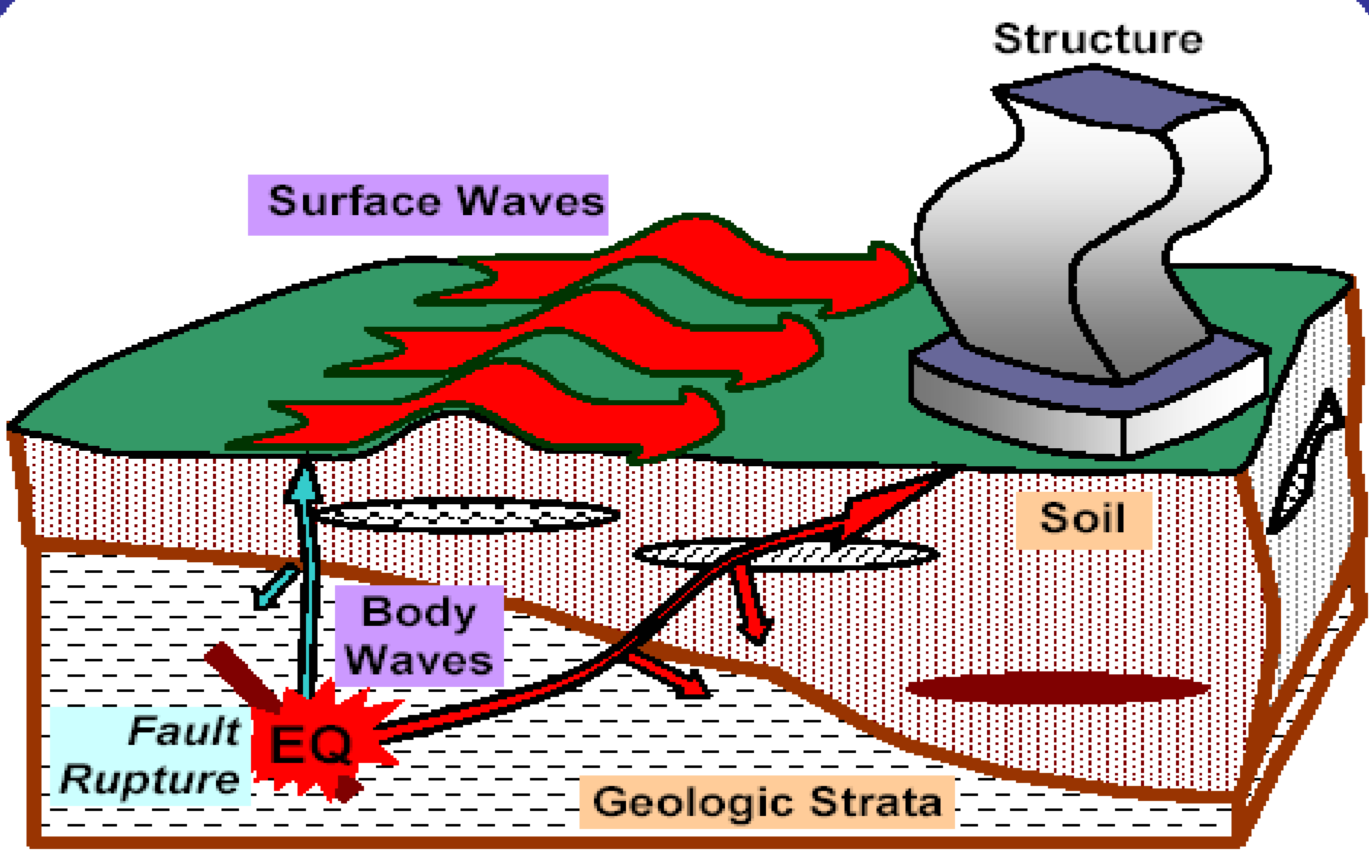

Figure 1: Arrival of Seismic Waves at a Site

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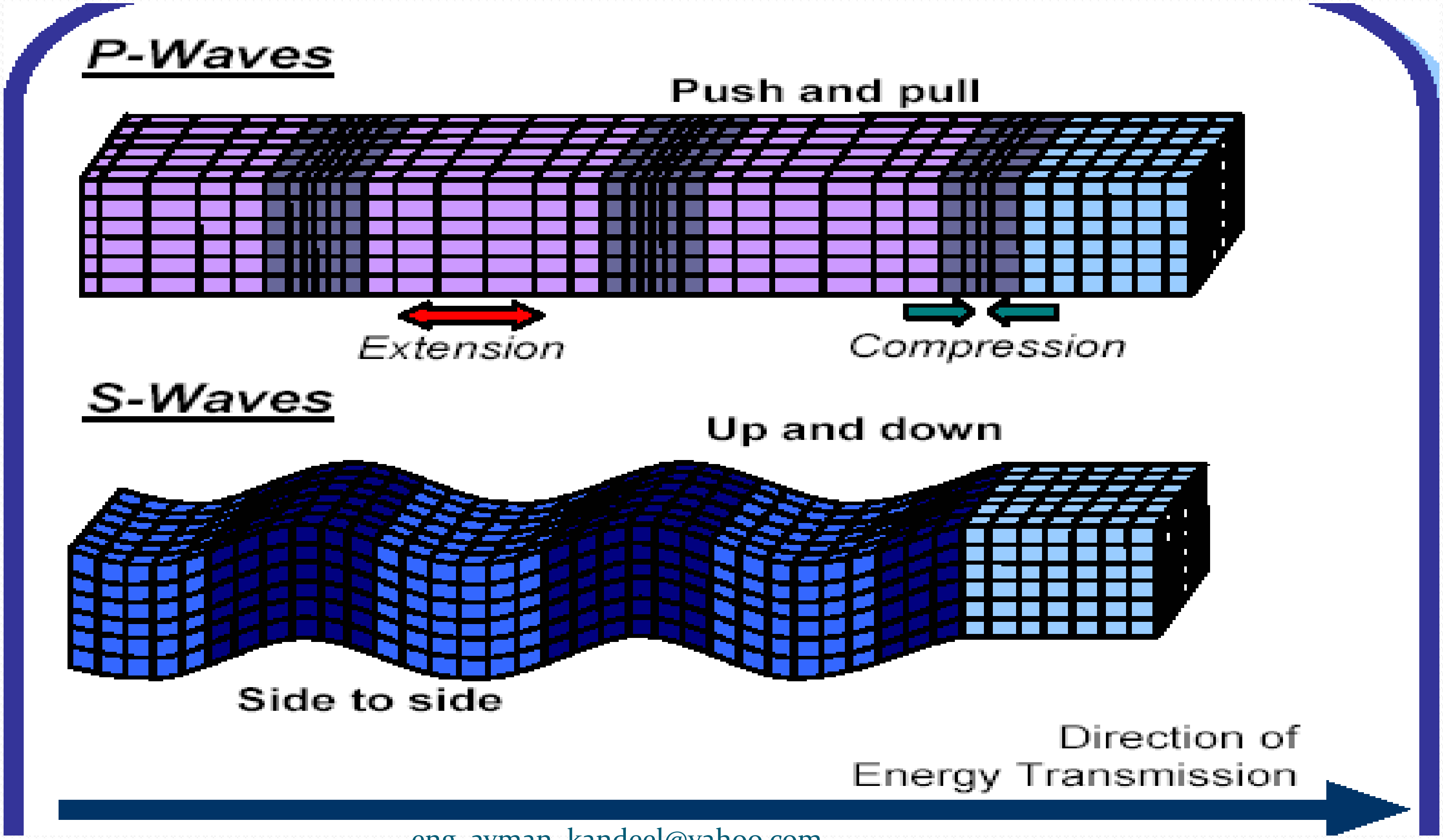
Under P-waves, material particles
undergo extensional and compressional strains along direction of energy transmission, but under S-waves, oscillate at right angles to it



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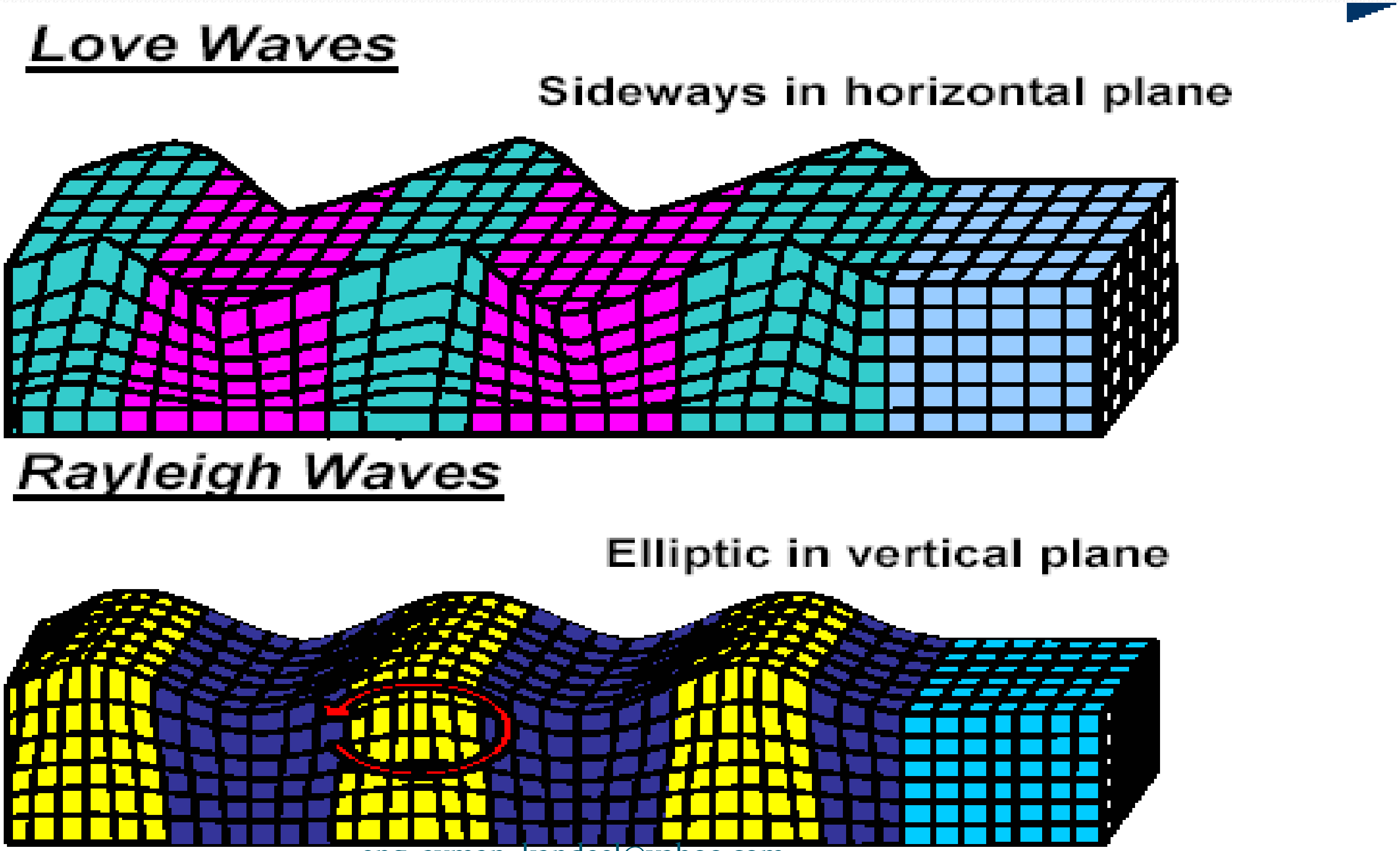
oscillate at right angles to it (Figure 2). Love waves cause surface motions similar to that by S-waves, but with no vertical component. Rayleigh wave makes a material particle oscillate in an elliptic path in the vertical plane (with horizontal motion along direction of energy transmission).



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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.

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Measuring Instruments

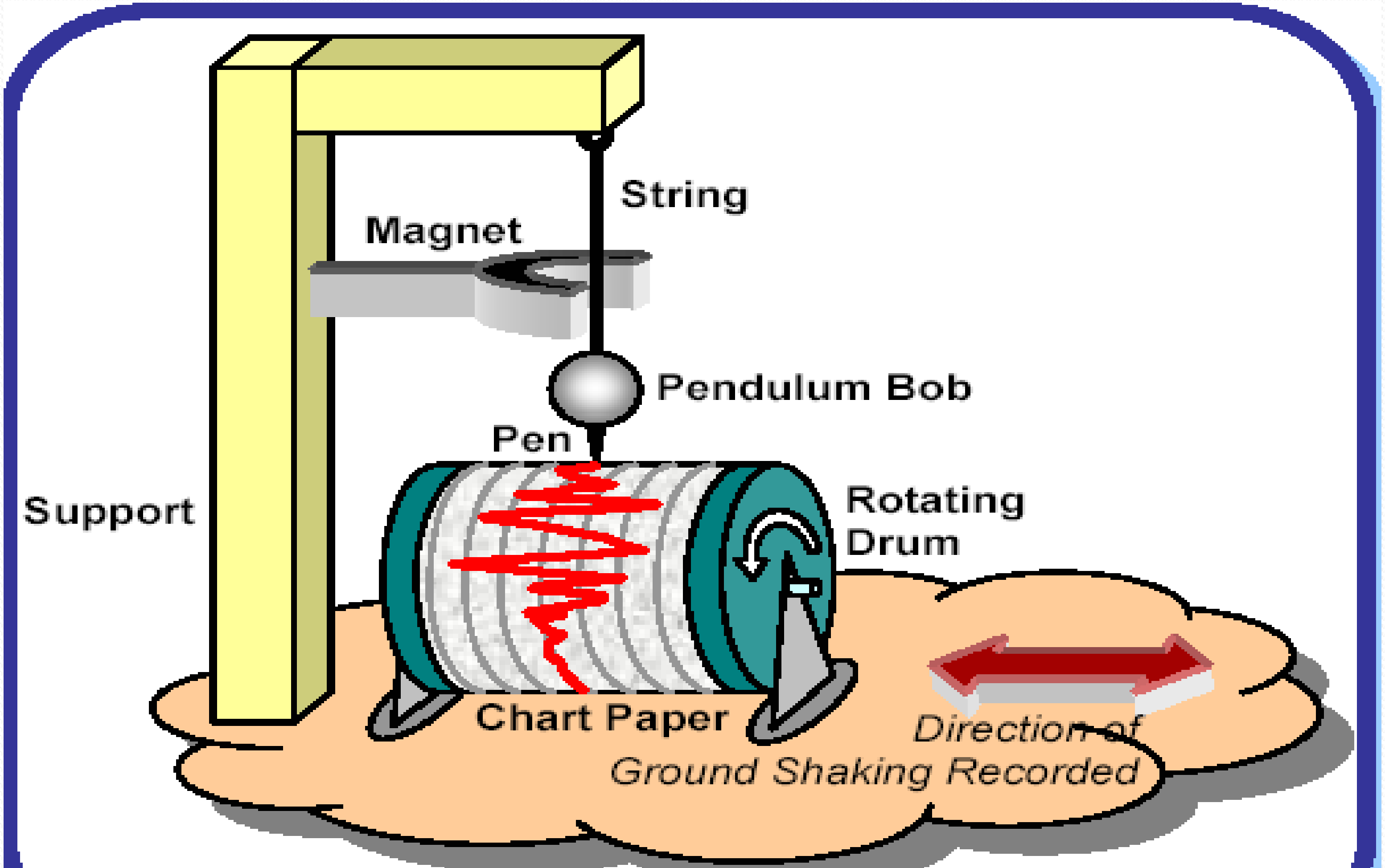

Figure 3: Schematic of *Early Seismograph*

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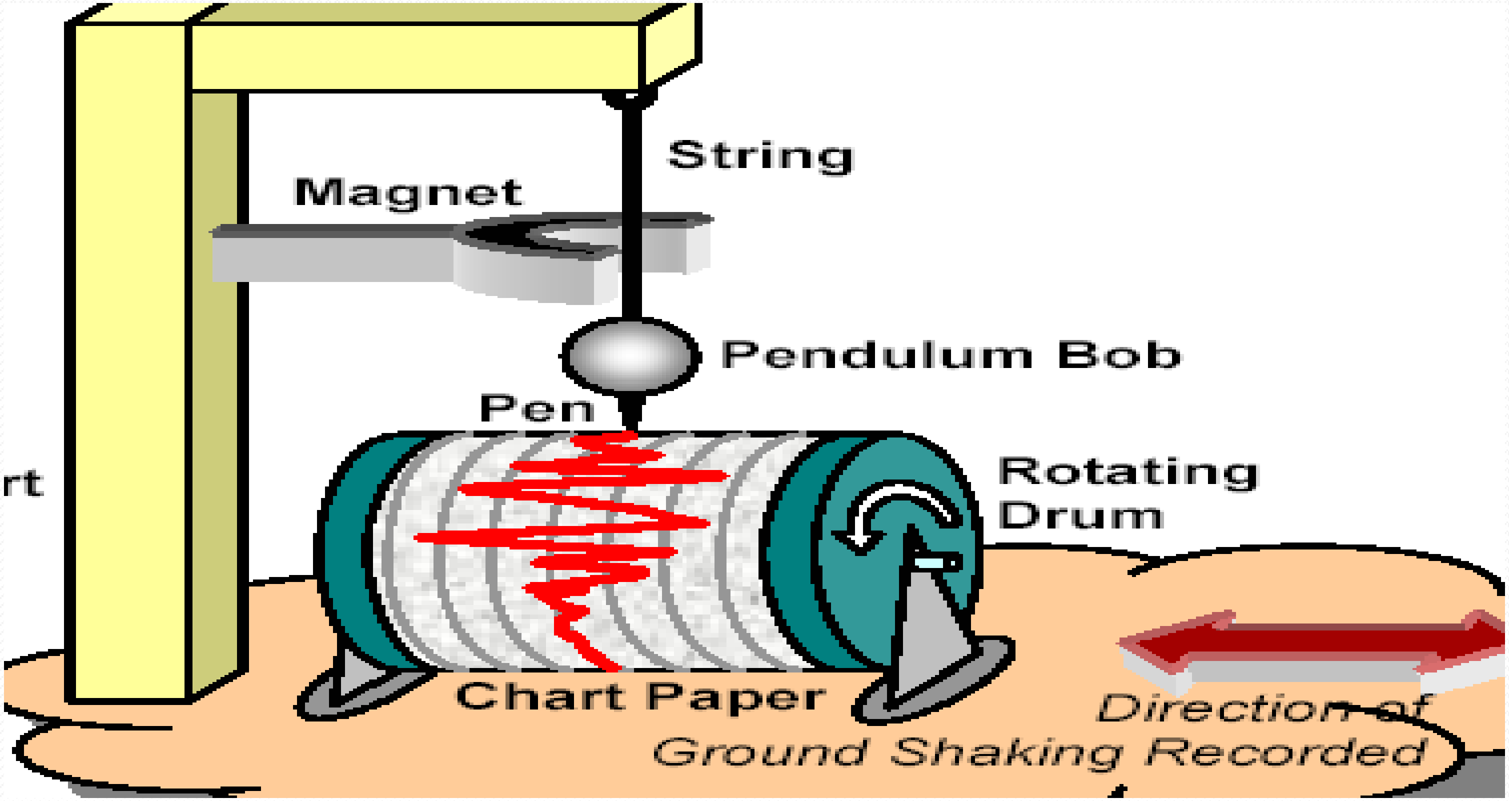
The instrument that measures earthquake shaking, a *seismograph*, has three components – the *sensor*, the *recorder* and the *timer*. The principle on which it works



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*.

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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

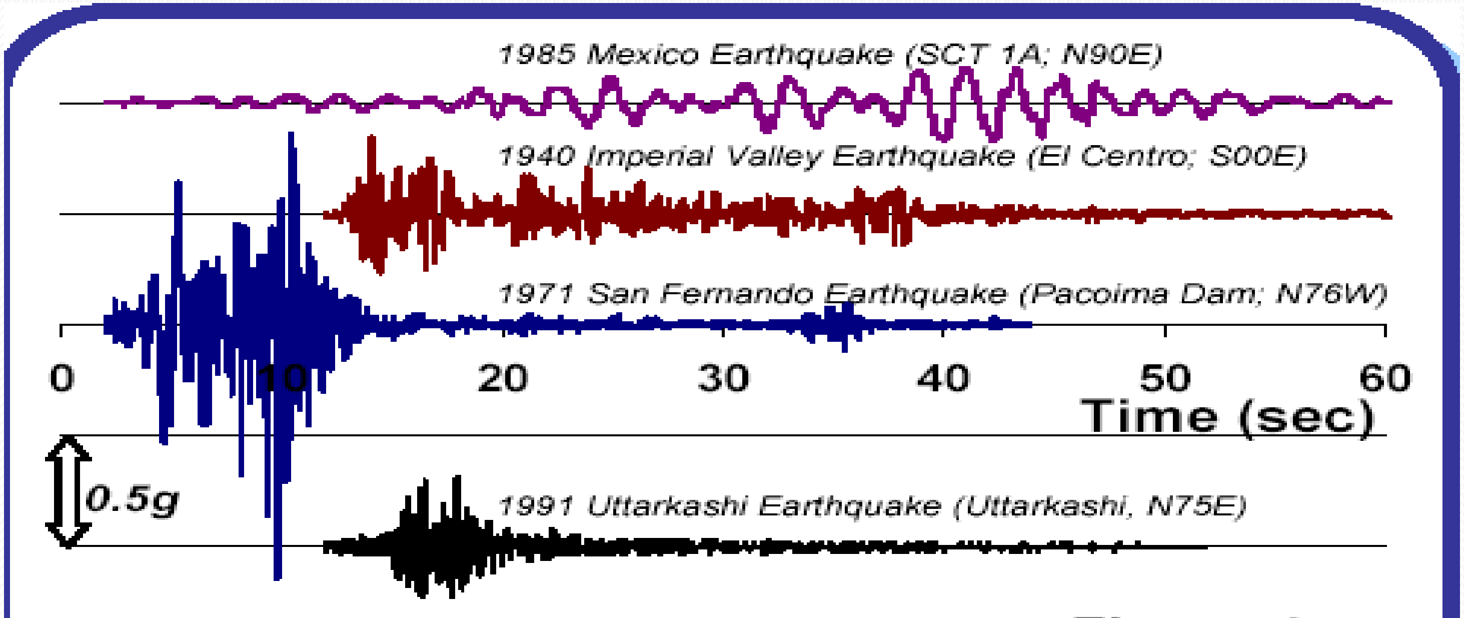

Figure 4::
Some typical recorded accelerograms

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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

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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*.

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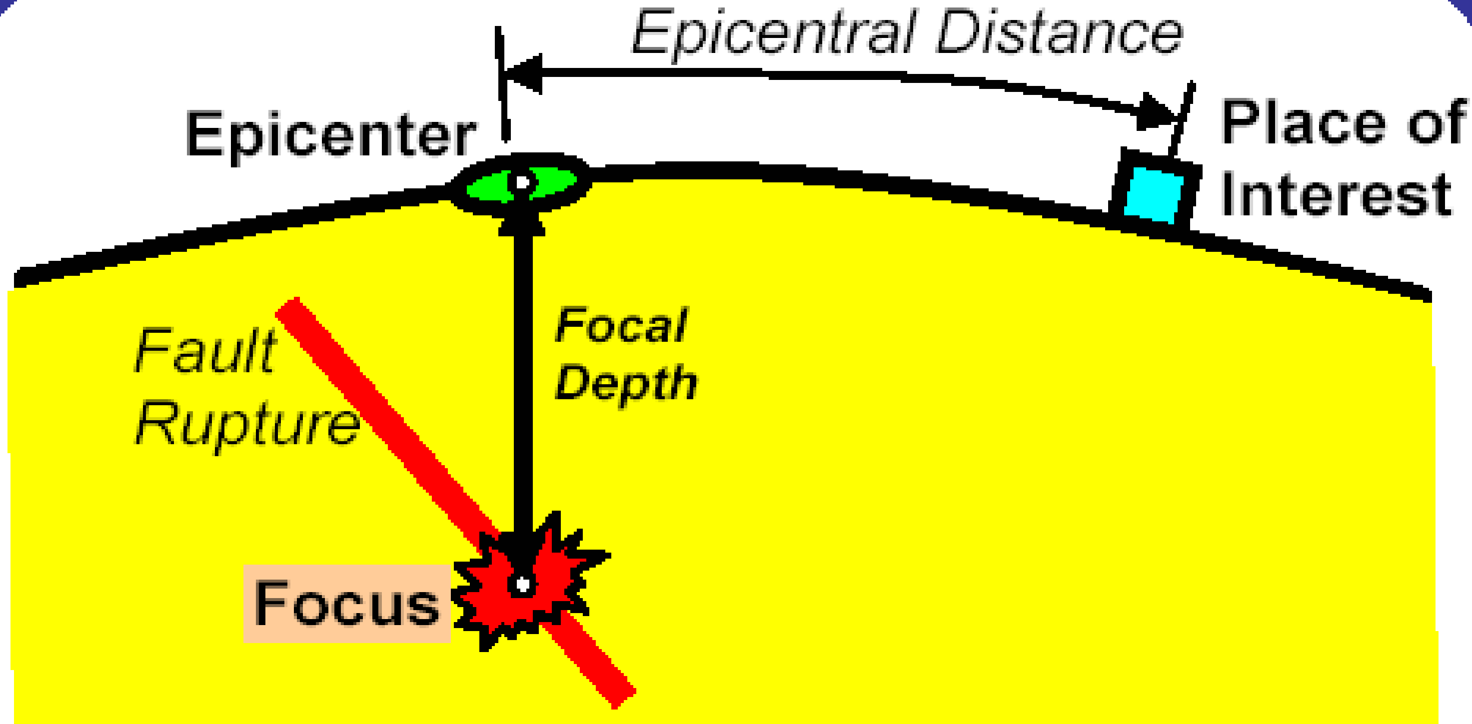

Figure 1: Basic terminology

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*.

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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.

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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 ($\approx 31 \times 31$) times that released in a $M5.7$ earthquake. Most of the energy

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 ($\approx 31 \times 31$) times that released in a $M5.7$ earthquake. Most of the energy

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!!)

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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

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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

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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

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

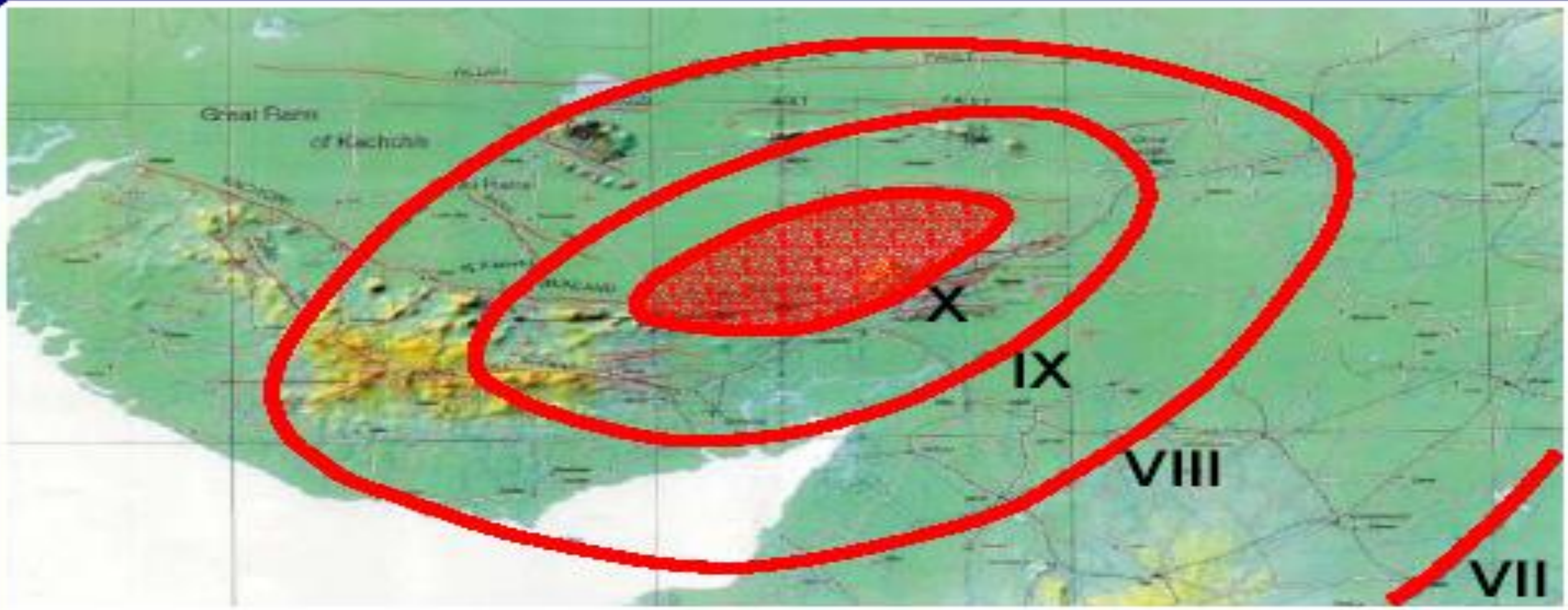

Figure 2: Isoseismal Map of the 2001 Bhuj (India) Earthquake (MSK Intensity)

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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

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

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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.

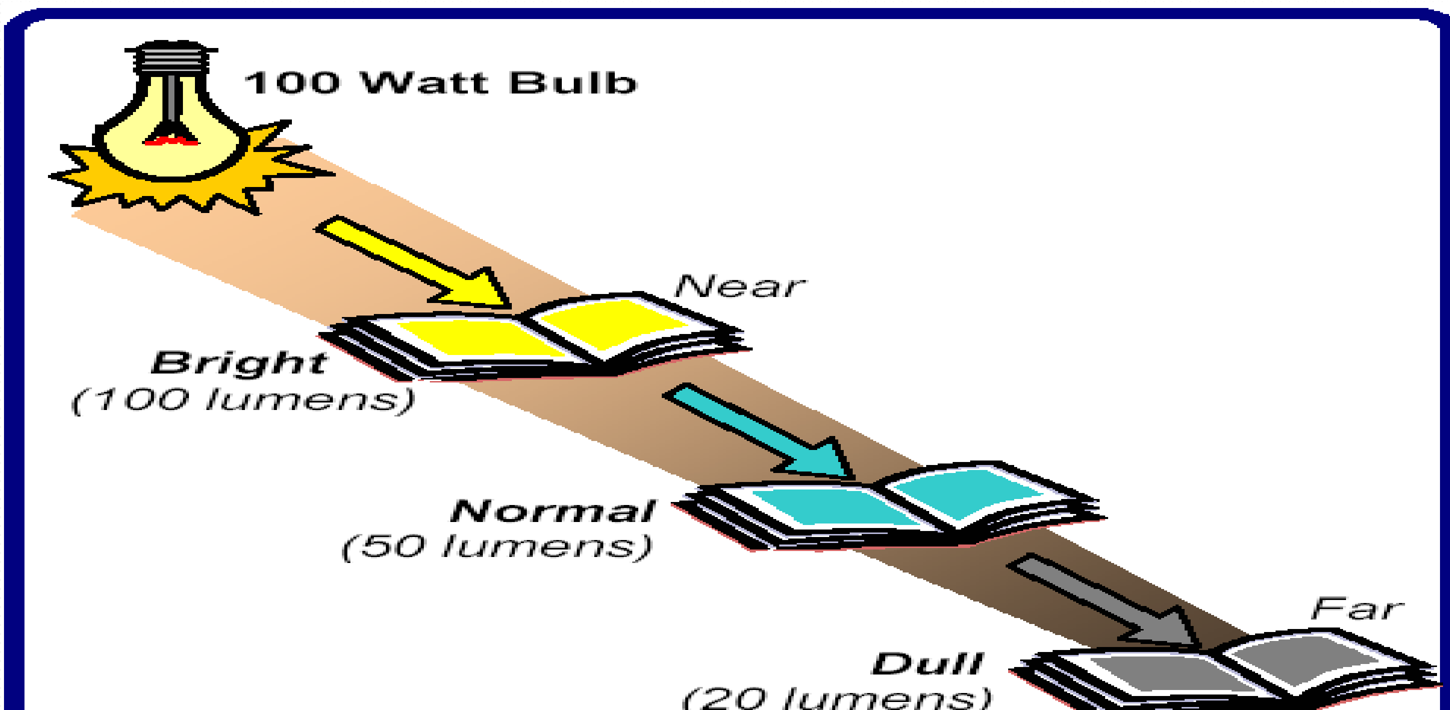

Figure 3: Reducing illumination with distance from an electric bulb

Where are the Seismic Zones in India?

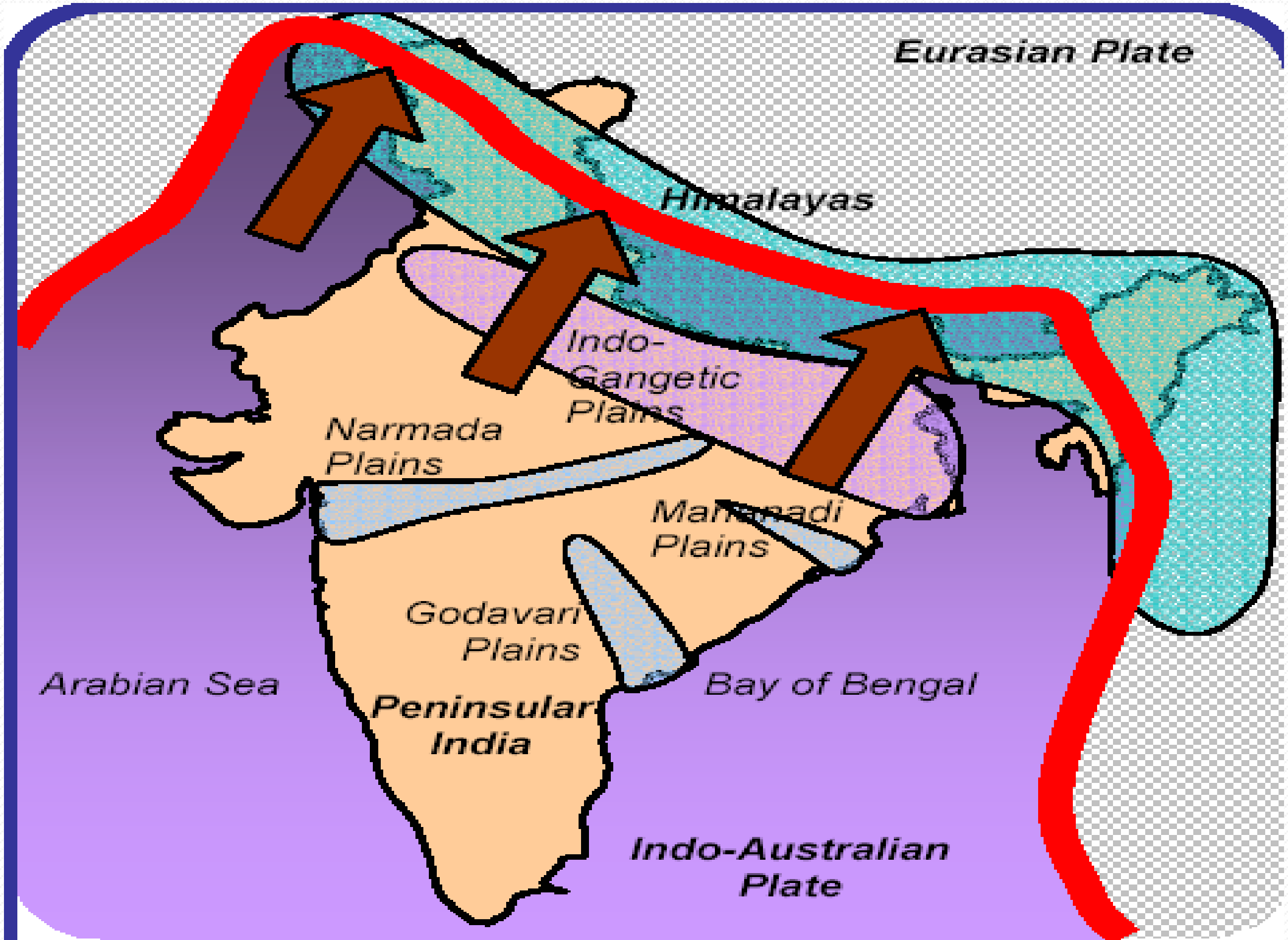

Figure 1: Geographical Layout and Tectonic Plate Boundaries at India

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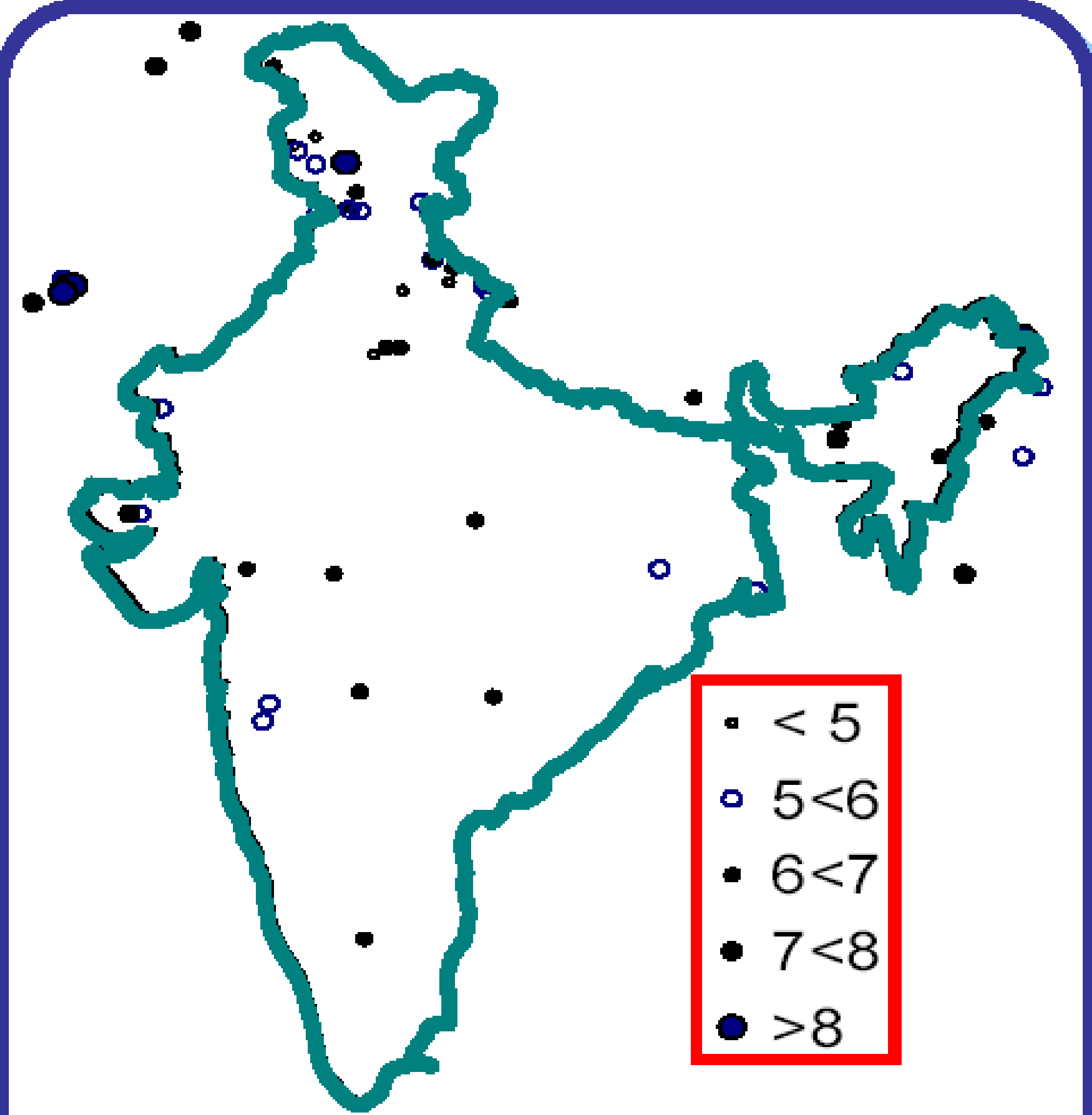

Figure 2: Some Past Earthquakes

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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

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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.

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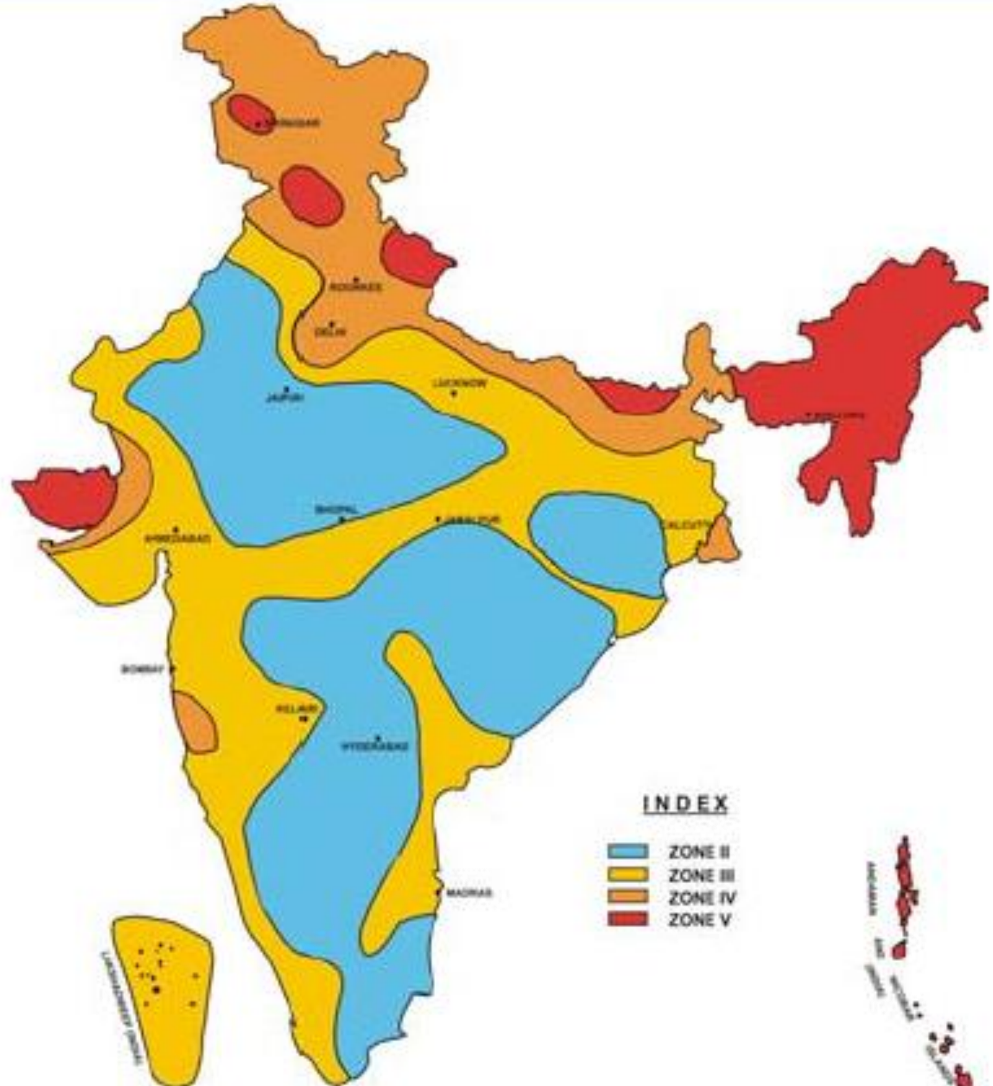

Figure 4: Indian Seismic Zone Map as per IS:1893 (Part 1)-2002

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What are the Seismic Effects on Structures?

Inertia Forces in Structures

Earthquake causes shaking of the ground. So a building resting on it will experience motion at its base. From *Newton's First Law of Motion*, even though the base of the building moves with the ground, the roof has a tendency to stay in its original position. But since the walls and columns are connected to it, they drag the roof along with them. *This is much like the situation that you are faced with when the bus you are standing in suddenly starts; your feet move with the bus, but your upper body tends to stay back making you fall backwards!!* This tendency to continue to remain in the

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backwards!! This tendency to continue to remain in the previous position is known as *inertia*. In the building, since the walls or columns are flexible, the motion of the roof is different from that of the ground (Figure 1).

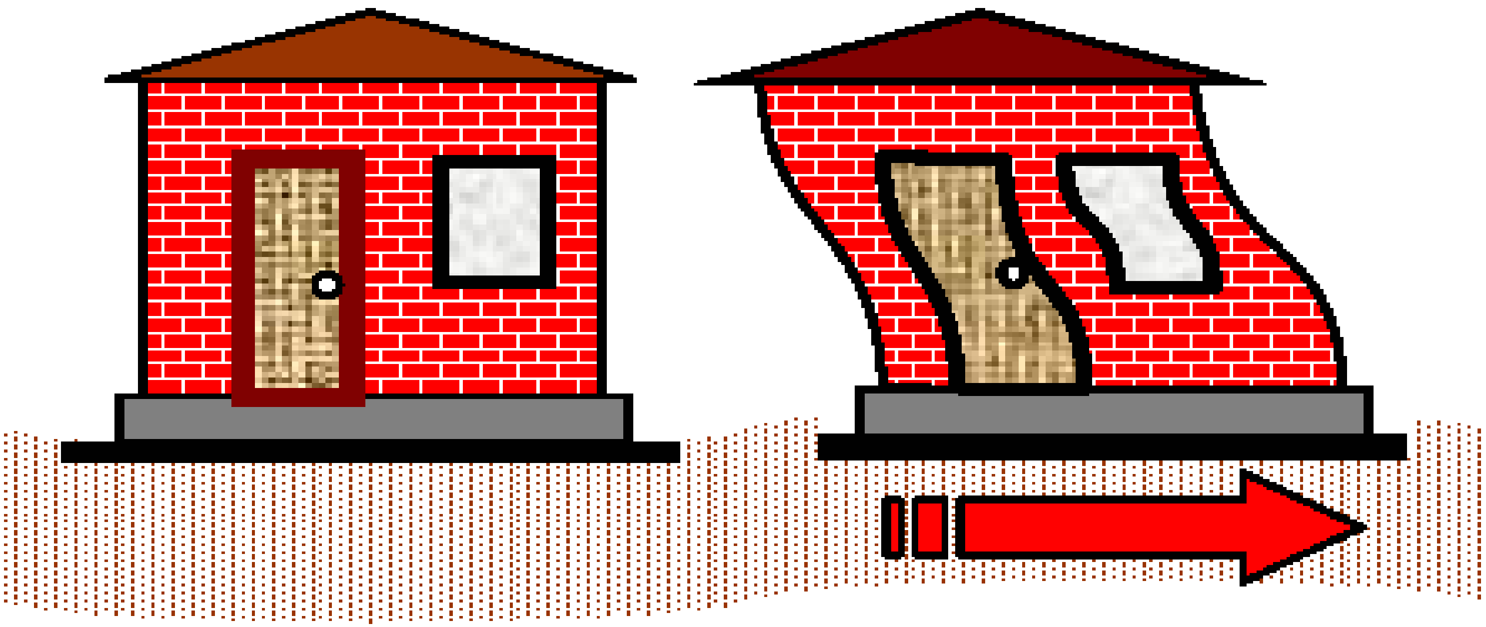

Figure 1: Effect of Inertia in a building when shaken at its base

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upper body. Similarly, when the ground moves, even the building is thrown backwards, and the roof experiences a force, called *inertia force*. If the roof has a mass *M* and experiences an acceleration *a*, then from *Newton's Second Law of Motion*, the *inertia force* F_I is mass *M* times acceleration *a*, and its direction is opposite to that of the acceleration. Clearly, more mass means higher inertia force. Therefore, lighter buildings sustain the earthquake shaking better.

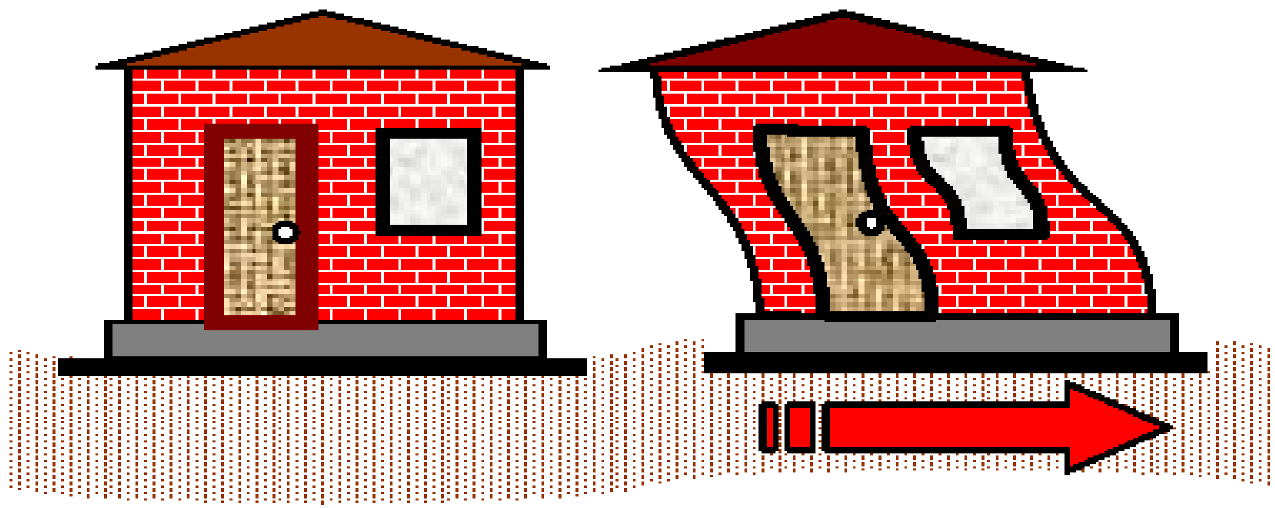

Figure 1: Effect of Inertia in a building when shaken at its base

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Effect of Deformations in Structures

The inertia force experienced by the roof is transferred to the ground via the columns, causing forces in columns. These forces generated in the columns can also be understood in another way. During earthquake shaking, the columns undergo relative movement between their ends. In Figure 2, this movement is shown as quantity **u** between the roof and the ground. But, given a free option, columns

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would like to come back to the straight vertical position, *i.e.*, columns resist deformations. In the straight vertical position, the columns carry no horizontal earthquake force through them. But, when forced to bend, they develop internal forces. The larger is the relative horizontal displacement **u** between the top and bottom of the column, the larger this internal force in columns. Also, the stiffer the columns are (*i.e.*, bigger is the column size), larger is this force. For this reason, these internal forces in the columns are called *stiffness forces*. In fact, the stiffness force in a column is the column stiffness times the relative displacement between its ends.

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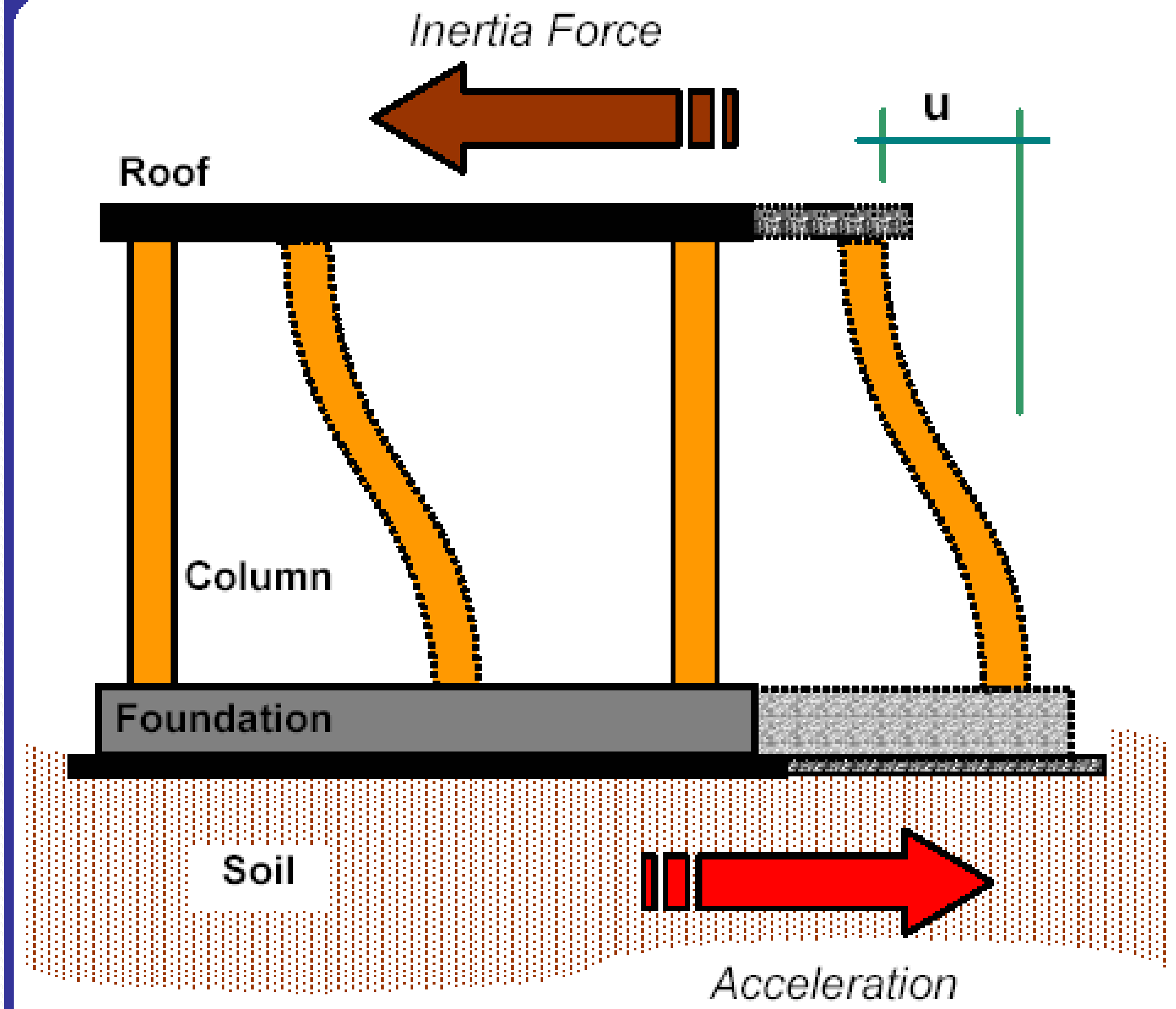

Figure 2: Inertia force and relative motion within a building

Horizontal and Vertical Shaking

Earthquake causes shaking of the ground in all three directions – along the two horizontal directions (*X and Y, say*), and the vertical direction (*Z, say*) (Figure

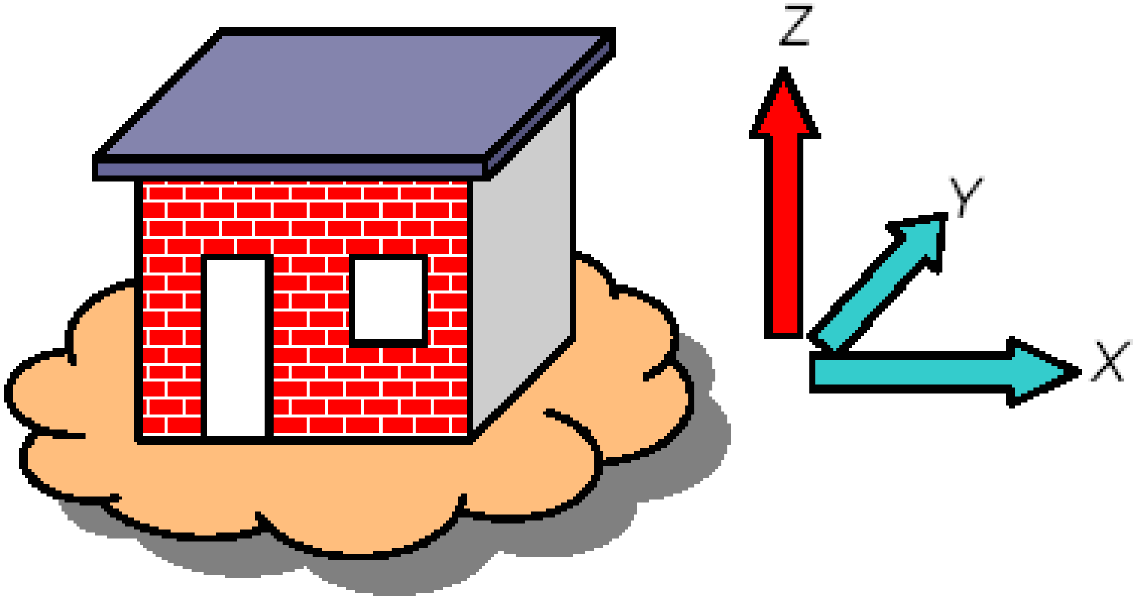

Figure 3: Principal directions of a building

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3). Also, during the earthquake, the ground shakes randomly *back and forth* (- and +) along each of these X, Y and Z directions. All structures are primarily designed to carry the gravity loads, *i.e.*, they are designed for a force equal to the mass *M* (this includes mass due to own weight and imposed loads) times the acceleration due to gravity *g* acting in the vertical downward direction (-Z). The downward force *Mg* is called the *gravity load*. The vertical acceleration during ground shaking either adds to or subtracts from the acceleration due to gravity. Since factors of safety are used in the design of structures to resist the gravity loads, usually most structures tend to be adequate against vertical shaking.

However, horizontal shaking along X and Y directions (both + and – directions of each) remains a concern. Structures designed for gravity loads, in general, may not be able to safely sustain the effects of horizontal earthquake shaking. Hence, it is necessary to ensure adequacy of the structures against horizontal earthquake effects.

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Flow of Inertia Forces to Foundations

Under horizontal shaking of the ground, horizontal inertia forces are generated at level of the mass of the structure (usually situated at the floor levels). These lateral inertia forces are transferred by the floor slab to the walls or columns, to the foundations, and finally to the soil system underneath (Figure 4). So, each of these structural elements (floor slabs, walls, columns, and foundations) and the connections between them must be designed to safely transfer these inertia forces through them.

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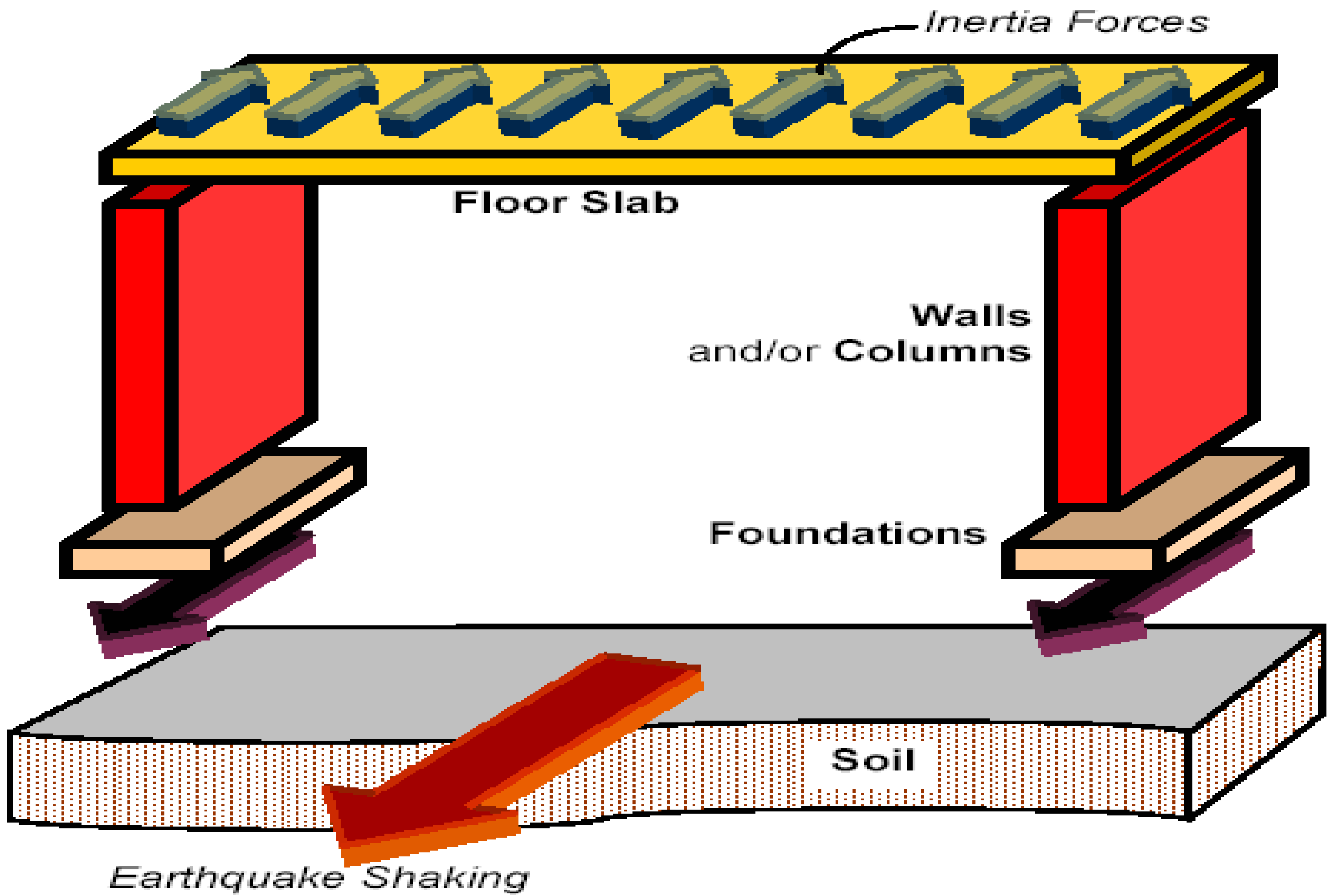

Figure 4: Flow of seismic inertia forces through all structural components.

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Walls or columns are the most critical elements in transferring the inertia forces. But, in traditional construction, floor slabs and beams receive more care and attention during design and construction, than walls and columns. Walls are relatively thin and often made of brittle material like masonry. They are poor in carrying horizontal earthquake inertia forces along the direction of their thickness. Failures of masonry walls

have been observed in many earthquakes in the past (*e.g.,* Figure 5a). Similarly, poorly designed and constructed reinforced concrete columns can be disastrous. The failure of the ground storey columns resulted in numerous building collapses during the 2001 Bhuj (India) earthquake (Figure 5b).

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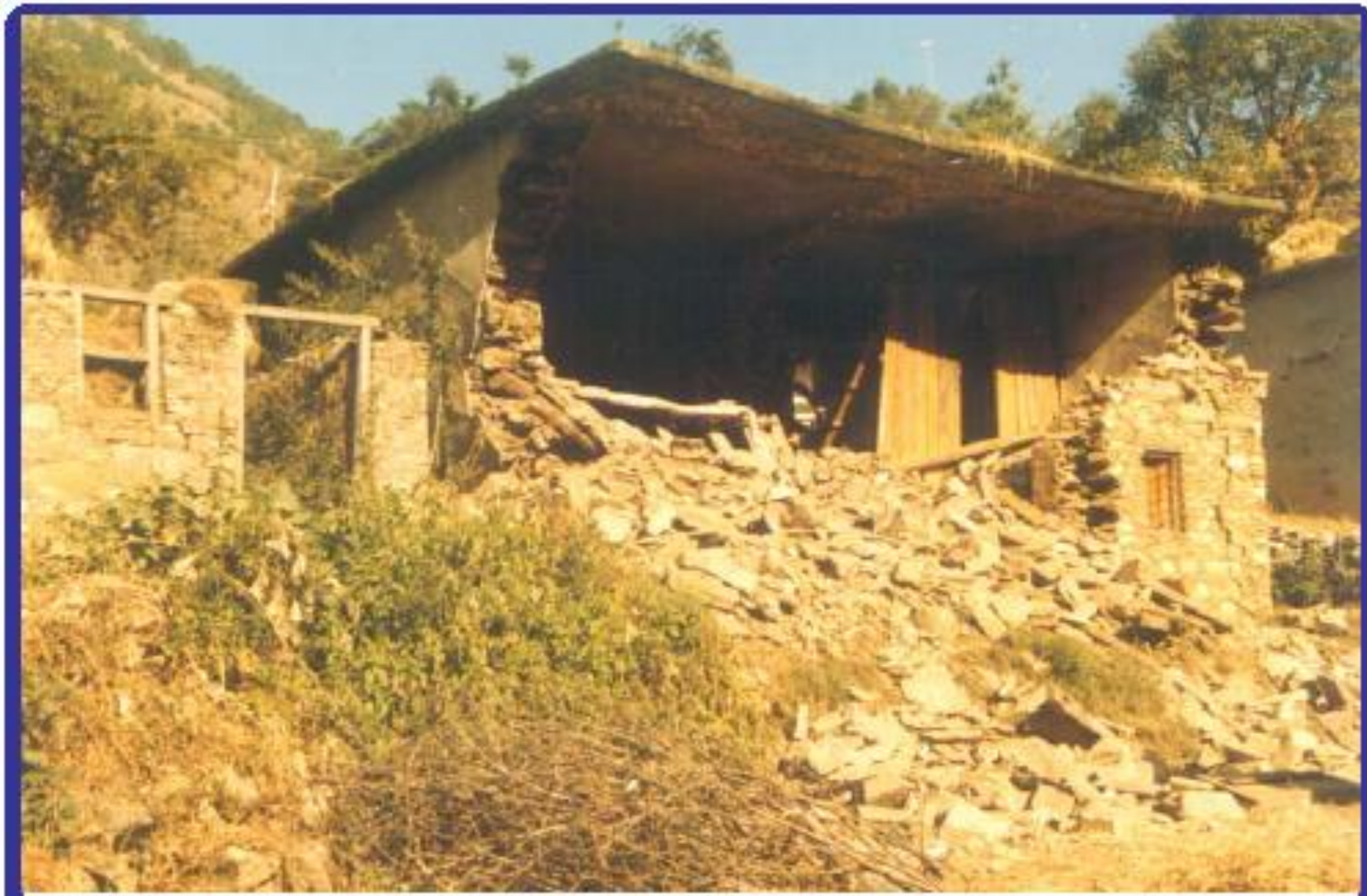

(a) Partial collapse of stone masonry walls during 1991 Uttarkashi (India) earthquake

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(b) Collapse of reinforced concrete columns (and building) during 2001 Bhuj (India) earthquake

Figure 5: Importance of designing walls/columns for horizontal earthquake forces.

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How Architectural Features Affect Buildings During Earthquakes?

Importance of Architectural Features

The behaviour of a building during earthquakes depends critically on its overall shape, size and geometry, in addition to how the earthquake forces are carried to the ground. Hence, at the planning stage itself, architects and structural engineers must work together to ensure that the unfavourable features are avoided and a good building configuration is chosen.

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Architectural Features

Size of Buildings: In tall buildings with large height-to-base size ratio (Figure 1a), the horizontal movement of the floors during ground shaking is large. In short but very long buildings (Figure 1b), the damaging effects during earthquake shaking are many. And, in buildings with large plan area like warehouses (Figure 1c), the horizontal seismic forces can be excessive to be carried by columns and walls.

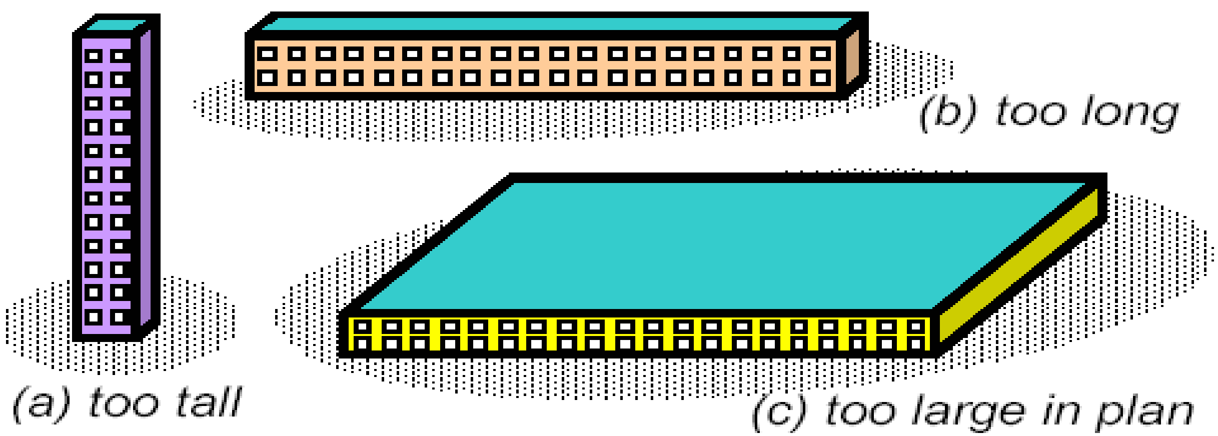

Figure 1: Buildings with one of their overall sizes much larger or much smaller than the other two, do not perform well during earthquakes.

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Horizontal Layout of Buildings: In general, buildings with simple geometry in plan (Figure 2a) have performed well during strong earthquakes. Buildings with re-entrant corners, like those U, V, H and + shaped in plan (Figure 2b), have sustained significant damage. Many times, the bad effects of these interior corners in the plan of buildings are avoided by making the buildings in two parts. For

example, an L-shaped plan can be broken up into two rectangular plan shapes using a separation joint at the junction (Figure 2c). Often, the plan is simple, but the columns/walls are not equally distributed in plan. Buildings with such features tend to twist during

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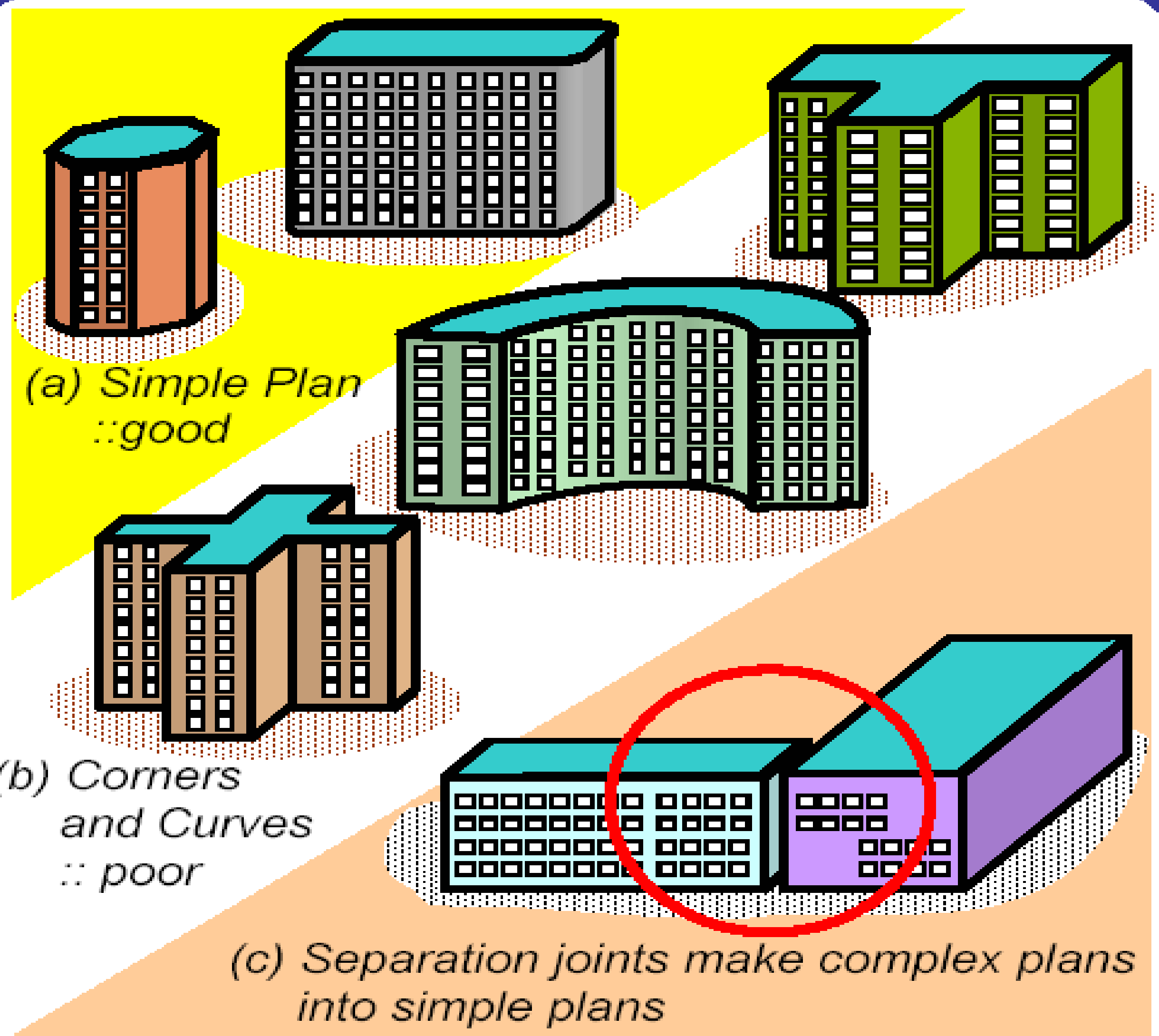

Figure 2: Simple plan shape buildings do well during earthquakes.

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Vertical Layout of Buildings: The earthquake forces developed at different floor levels in a building need to be brought down along the height to the ground by the shortest path; any deviation or discontinuity in this load transfer path results in poor performance of the building. Buildings with vertical setbacks (like the hotel buildings with a few storeys wider than the rest) cause a sudden jump in earthquake forces at the level of discontinuity (Figure 3a). Buildings that have fewer columns or walls in a particular storey or with unusually tall storey (Figure

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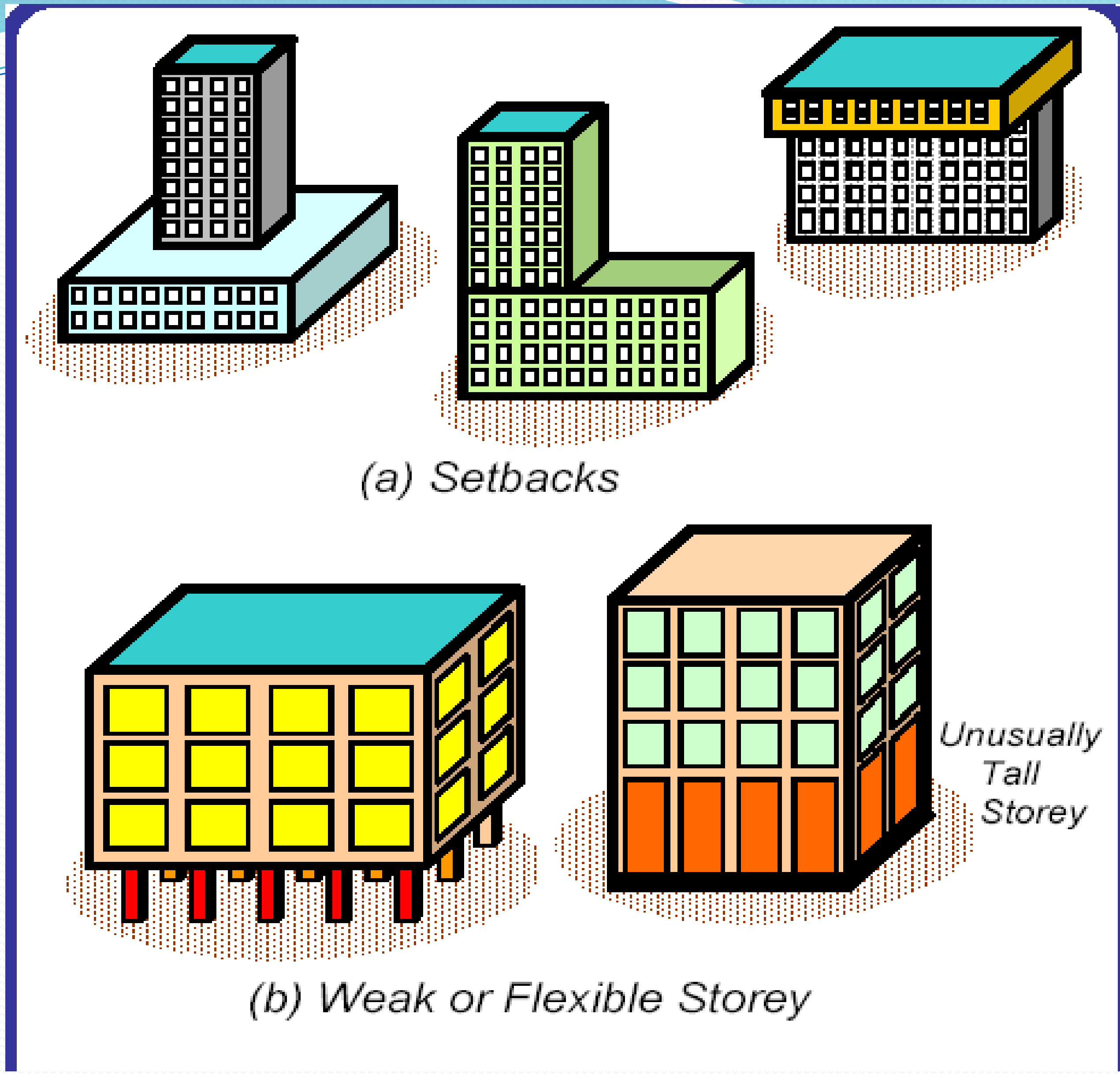

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Buildings on slopy ground have unequal height columns along the slope, which causes ill effects like twisting and damage in shorter columns (Figure 3c). Buildings with columns that hang or float on beams at an intermediate storey and do not go all the way to the foundation, have discontinuities in the load transfer path (Figure 3d). Some buildings have reinforced concrete walls to carry the earthquake loads to the foundation. Buildings, in which these walls do not go all the way to the ground but stop at an upper level, are liable to get severely damaged during earthquakes.

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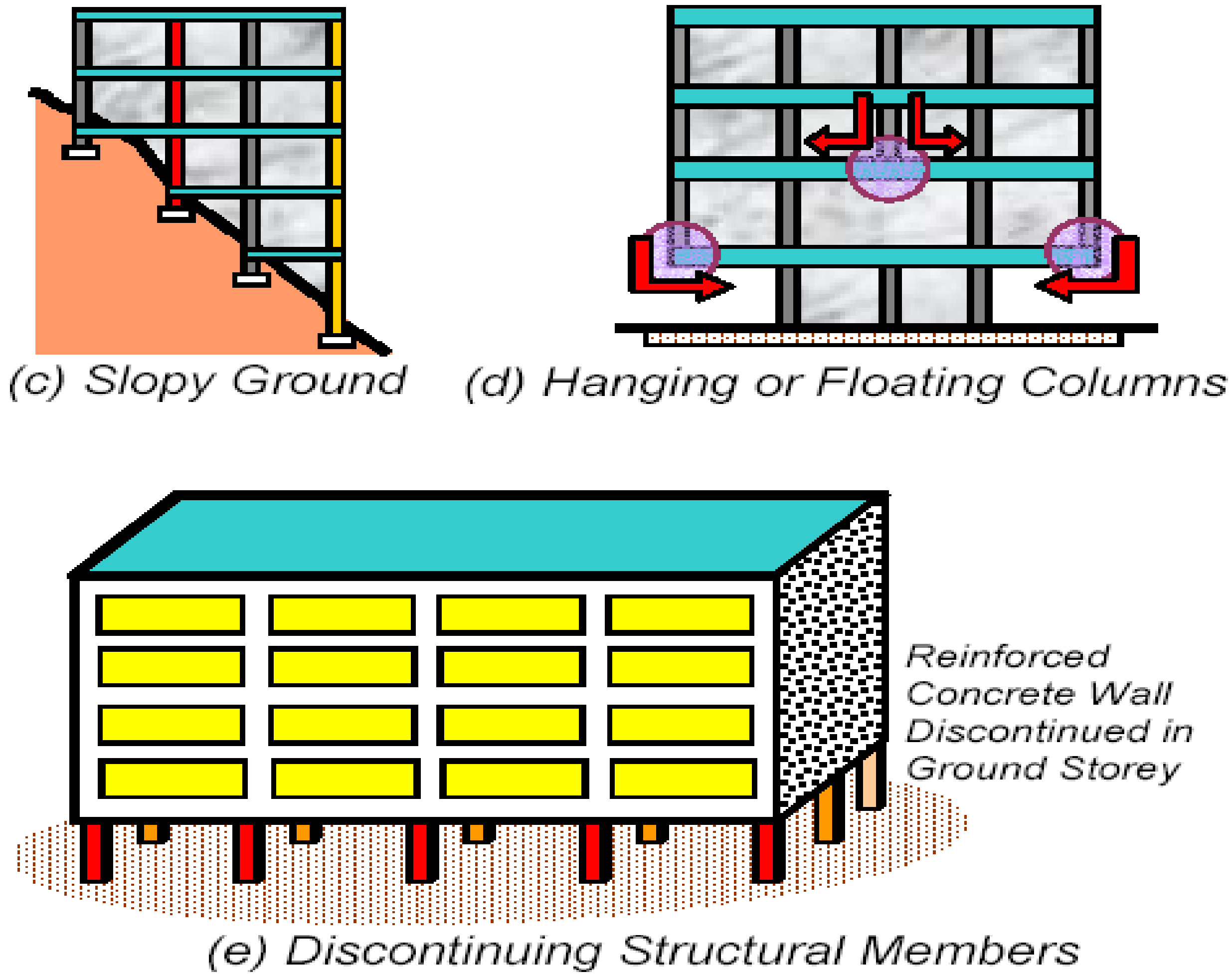

Figure 3: Sudden deviations in load transfer path along the height lead to poor performance of buildings.

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Adjacency of Buildings: When two buildings are too close to each other, they may pound on each other during strong shaking. With increase in building height, this collision can be a greater problem. When building heights do not match (Figure 4), the roof of the shorter building may pound at the mid-height of the column of the taller one; this can be very dangerous.

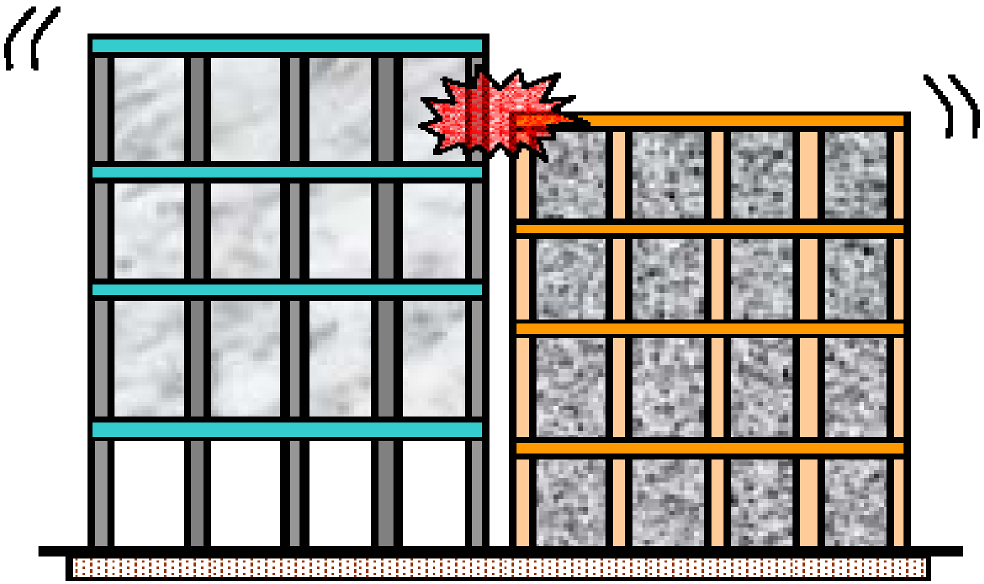

Figure 4: Pounding can occur between adjoining buildings due to horizontal vibrations of the two buildings.

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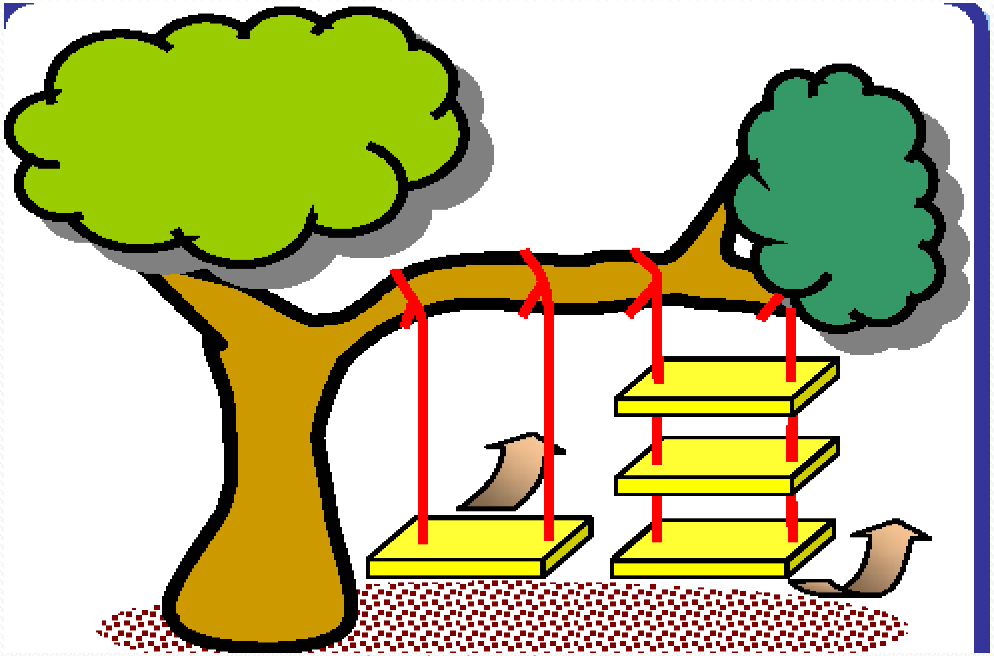
7 How Buildings Twist During Earthquakes?

Why a Building Twists

In your childhood, you must have sat on a rope swing - a wooden cradle tied with coir ropes to the sturdy branch of an old tree. The more modern versions of these swings can be seen today in the children's parks in urban areas; they have a plastic cradle tied with steel chains to a steel framework.



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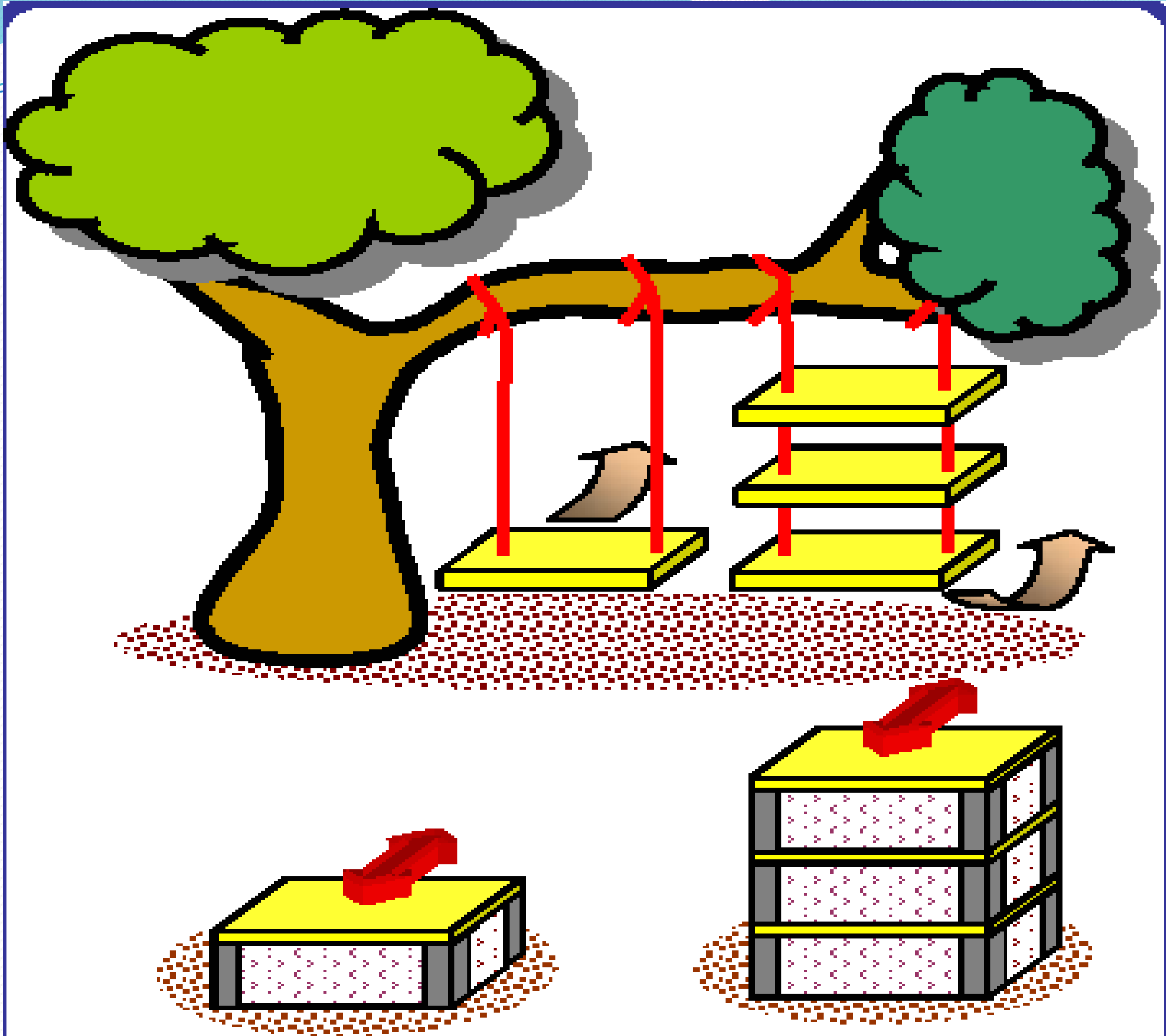

(a) Single-storey building (b) Three-storey building

Figure 1: Rope swings and buildings, both swing back-and-forth when shaken horizontally. The former are hung from the top, while the latter are raised from the ground.

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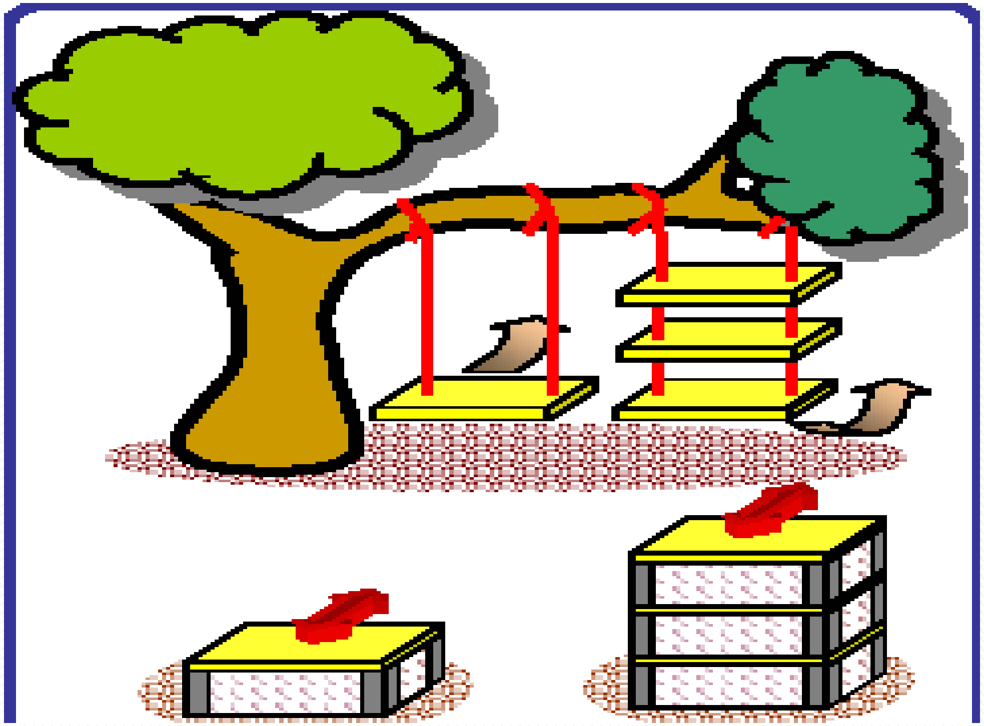
Consider a rope swing that is tied identically with two equal ropes. It swings equally, when you sit in the middle of the cradle. Buildings too are like these rope swings; just that they are inverted swings (Figure 1). The vertical walls and columns are like the ropes, and the floor is like the cradle. Buildings vibrate back and forth during earthquakes. Buildings with more than one storey are like rope swings with more than one cradle.



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Thus, if you see from sky, a building with identical vertical members and that are uniformly placed in the two horizontal directions, when shaken at its base in a certain direction, swings back and forth such that all points on the floor move horizontally by the same amount in the direction in which it is shaken (Figure 2).

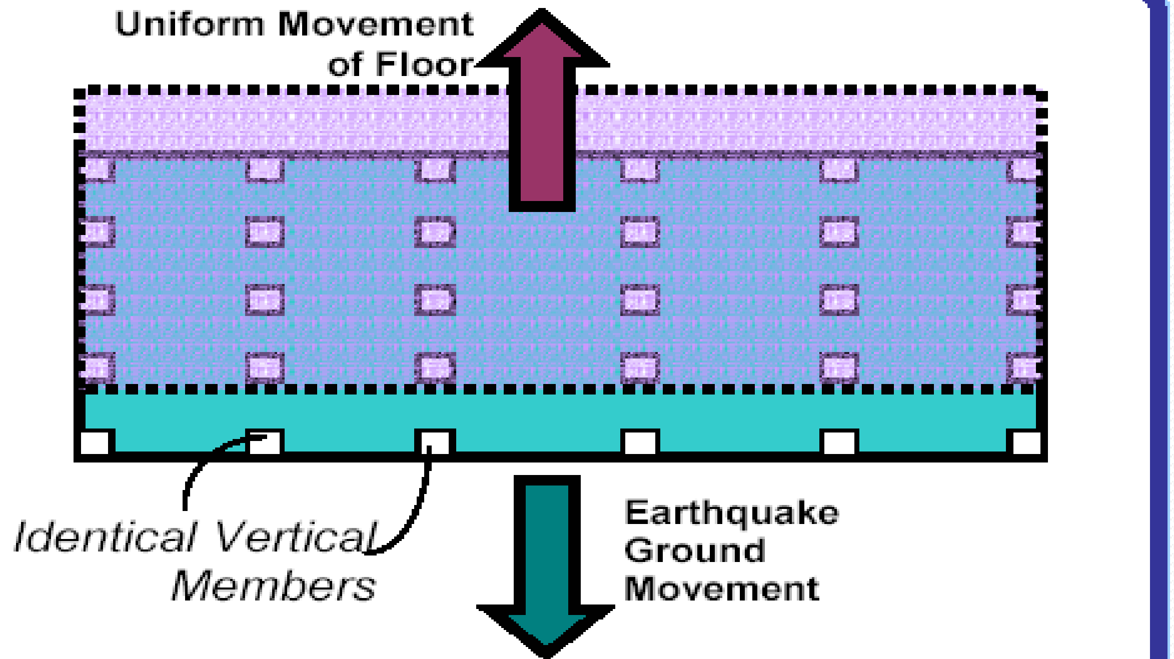

Figure 2: Identical vertical members placed uniformly in plan of building cause all points on the floor to move by same amount.

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Again, let us go back to the rope swings on the tree: if you sit at one end of the cradle, it *twists* (*i.e.*, moves more on the side you are sitting). This also happens sometimes when more of your friends bunch together and sit on one side of the swing. Likewise, if the mass on the floor of a building is more on one side (for instance, one side of a building may have a storage or a library), then that side of the building moves more under ground movement (Figure 3). This building moves such that its floors displace horizontally as well as rotate.

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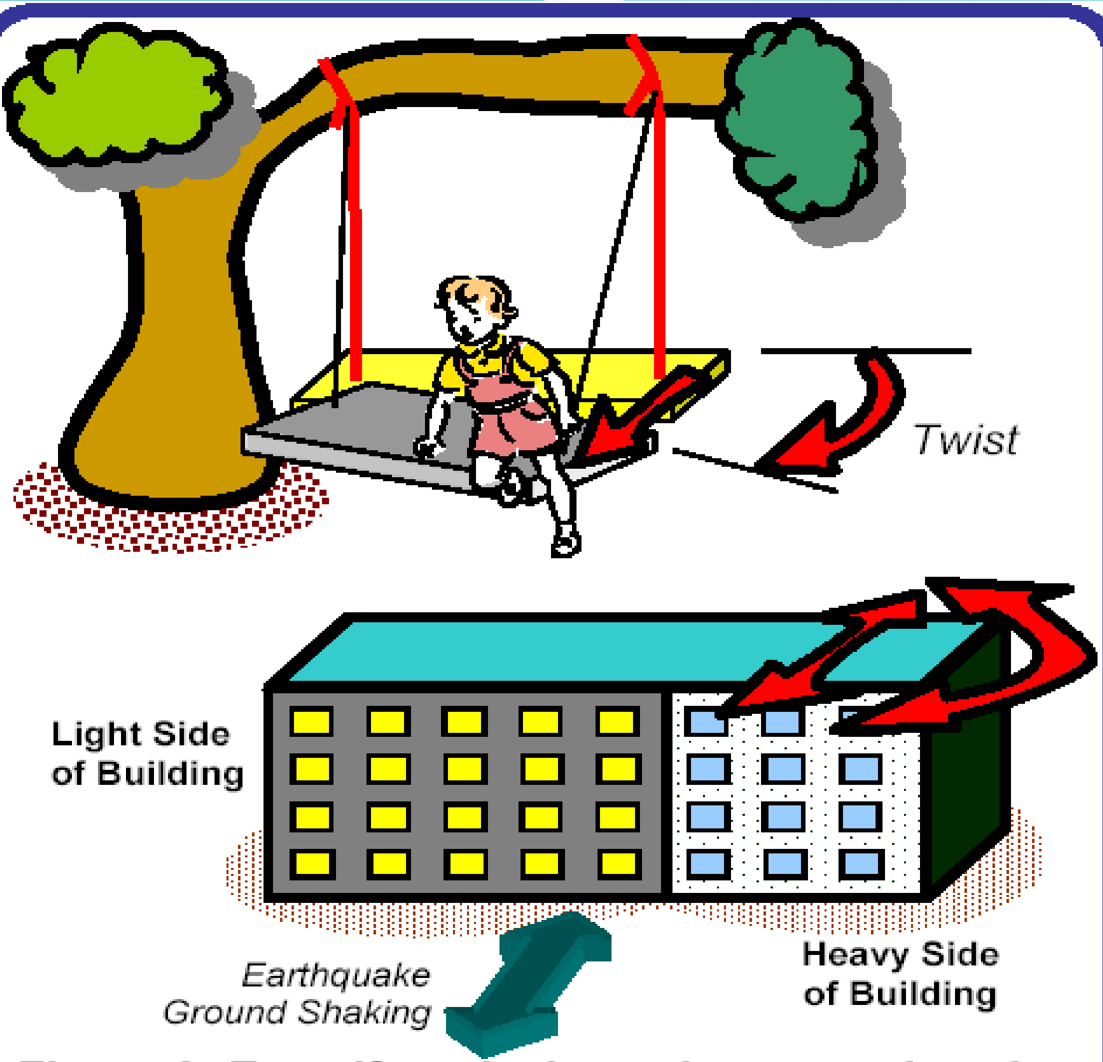

Figure 3: Even if vertical members are placed uniformly in plan of building, more mass on one side causes the floors to twist.

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Once more, let us consider the rope swing on the tree. This time let the two ropes with which the cradle is tied to the branch of the tree be different in length. Such a swing also *twists* even if you sit in the middle (Figure 4a). Similarly, in buildings with unequal vertical members (*i.e.,* columns and/or walls) also the floors twist about a vertical axis (Figure 4b) and displace horizontally. Likewise, buildings, which have walls only on two sides (or one side) and thin columns along the other, twist when shaken at the ground level (Figure 4c).

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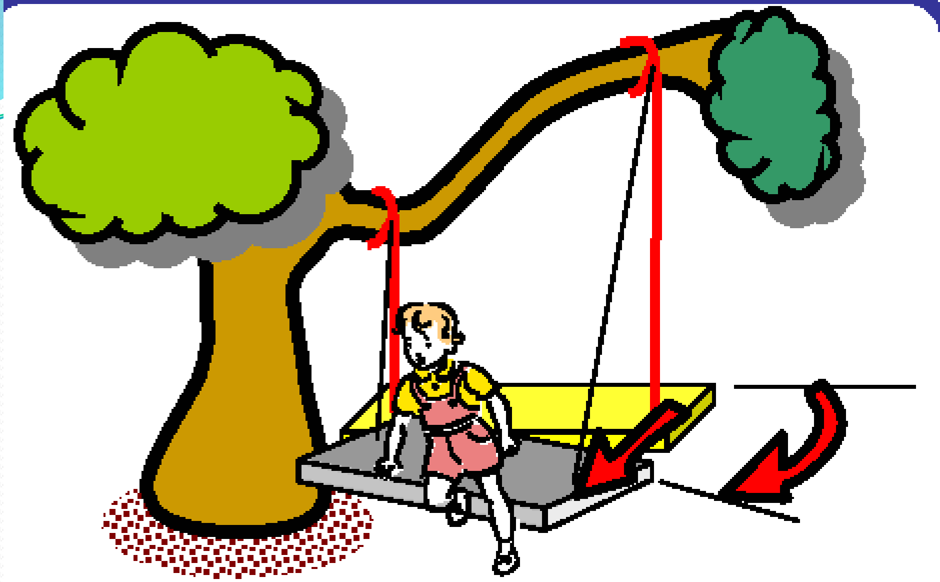
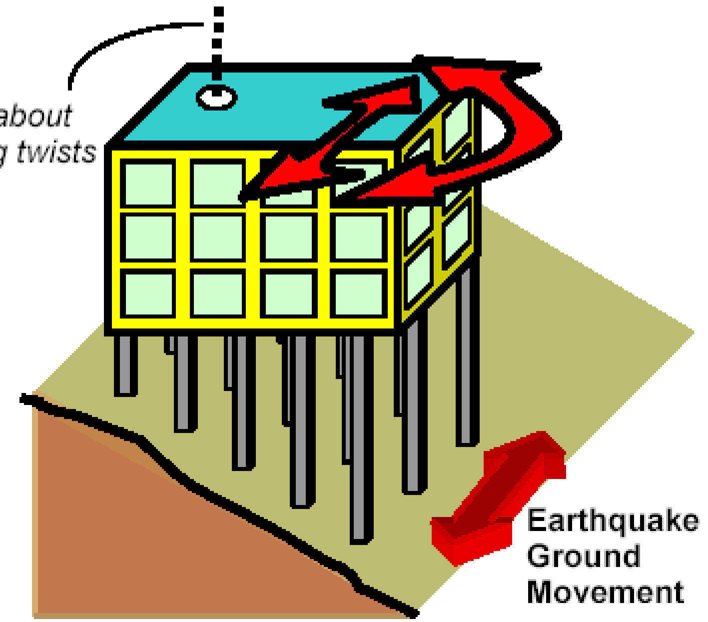


(a) Swing with unequal ropes



(b) Building on slopy ground

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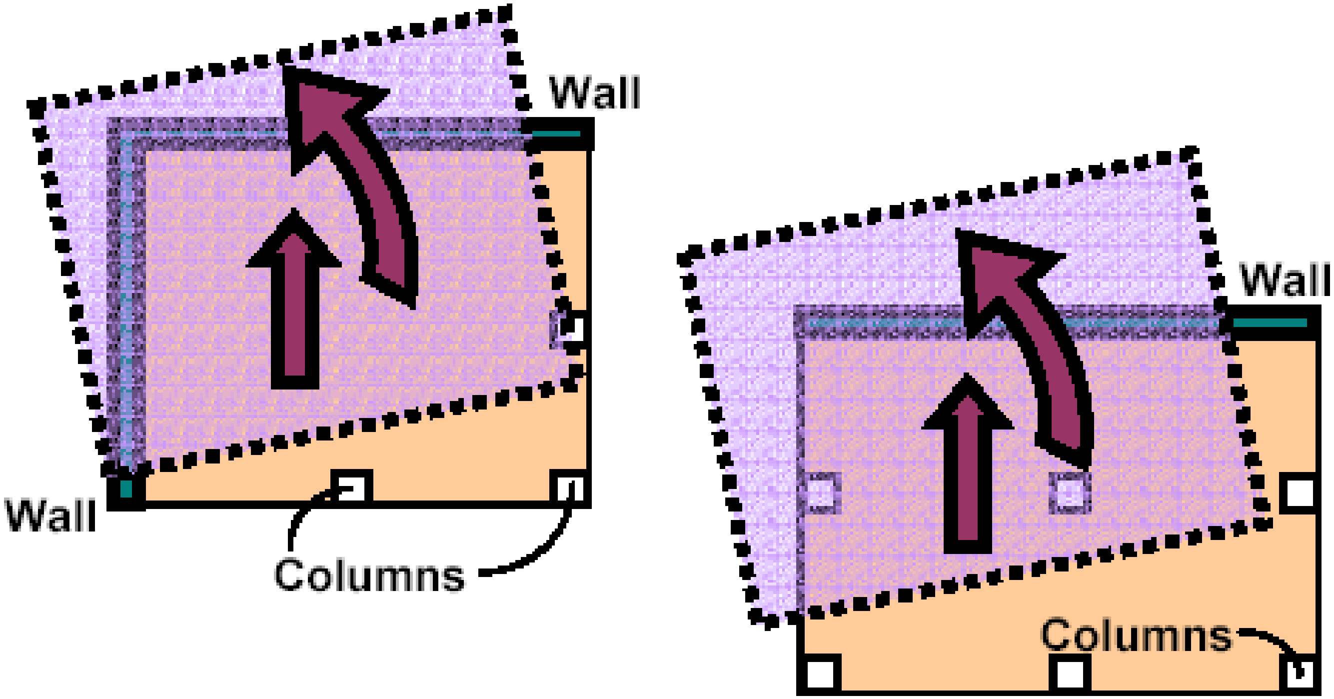

(c) Buildings with walls on two/one sides (in plan)

Figure 4: Buildings have unequal vertical members; they cause the building to twist about a vertical axis.

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Buildings that are irregular shapes in plan tend to twist under earthquake shaking. For example, in a propped overhanging building (Figure 5), the overhanging portion swings on the relatively slender columns under it. The floors twist and displace horizontally.

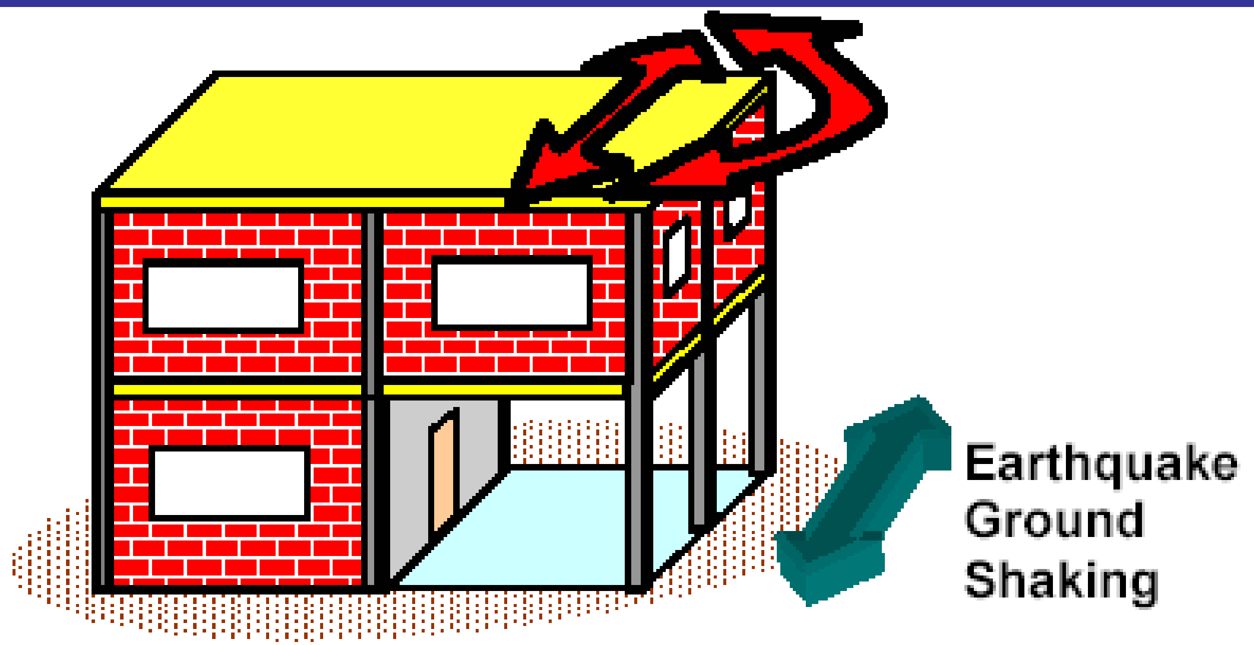

Figure 5: One-side open ground storey building twists during earthquake shaking.

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What Twist does to Building Members

Twist in buildings, called *torsion* by engineers, makes different portions at the same floor level to move horizontally by different amounts. This induces more damage in the columns and walls on the side that moves more (Figure 6). Many buildings have been severely affected by this excessive torsional behaviour during past earthquakes. It is best to minimize (if not completely avoid) this twist by ensuring that buildings have symmetry in plan (*i.e.,* uniformly distributed mass and uniformly placed vertical members). If this twist cannot be avoided, special calculations need to be done to account for this additional shear forces in the design of buildings; the Indian seismic code (IS 1893, 2002) has provisions for such calculations. But, for sure, buildings with twist will perform poorly during strong earthquake shaking.

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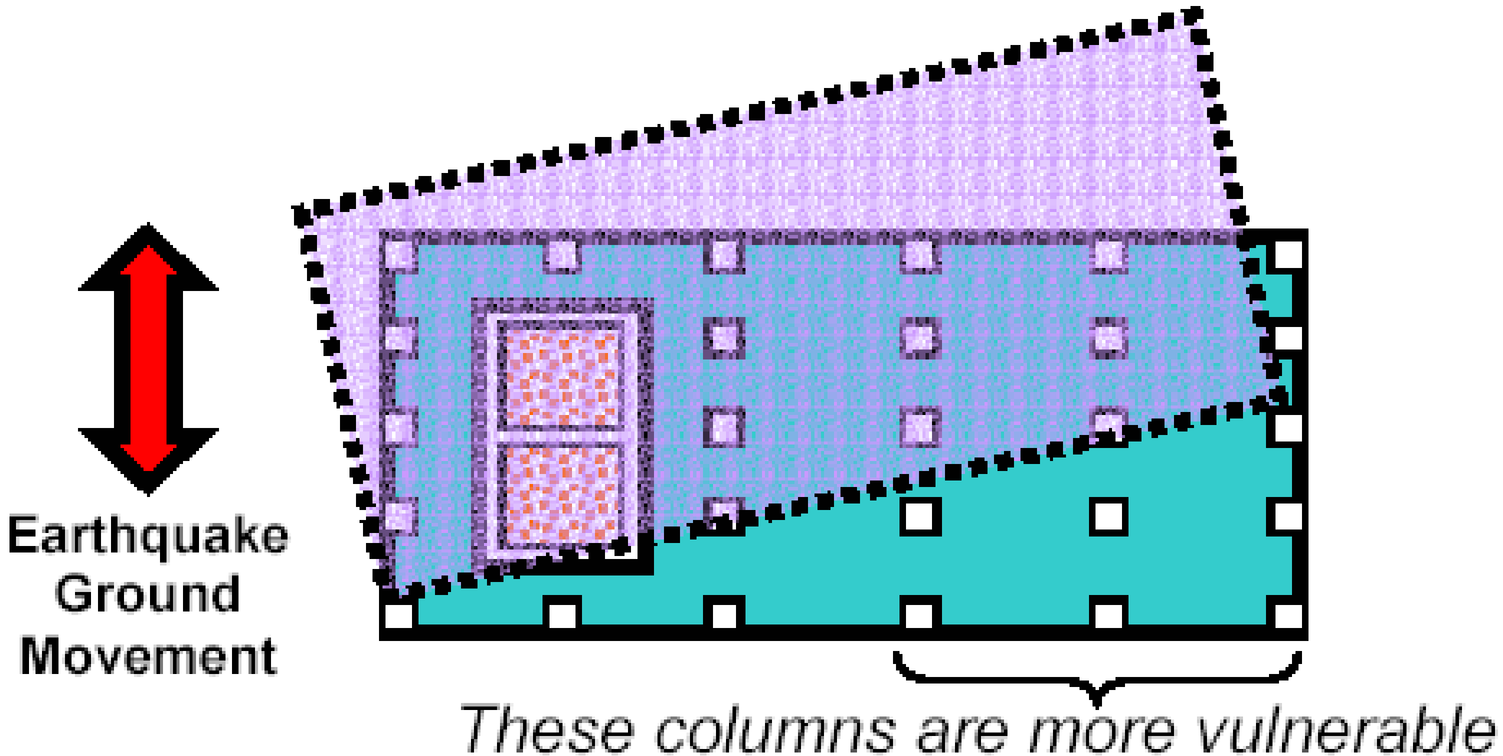

Figure 6: Vertical members of buildings that move more horizontally sustain more damage.

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8 What is the Seismic Design Philosophy for Buildings?

The Earthquake Problem

Severity of ground shaking at a given location during an earthquake can be *minor, moderate* and *strong*. Relatively speaking, minor shaking occurs frequently, moderate shaking occasionally and strong shaking rarely. For instance, on average annually about 800 earthquakes of magnitude 5.0-5.9 occur in the world while the number is only about 18 for magnitude range 7.0-7.9 (see Table 1 of IITK-BMTPC Earthquake Tip 03 at *www.nicee.org*). So, should we design and construct a building to resist that *rare* earthquake shaking that may come only once in 500 years or even once in 2000 years at the chosen project site, even though the life of the building itself may be only 50 or 100 years? Since it costs money to provide additional earthquake safety in buildings, a conflict

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arises: *Should we do away with the design of buildings for earthquake effects?* Or *should we design the buildings to be "earthquake proof" wherein there is no damage during the strong but rare earthquake shaking?* Clearly, the former approach can lead to a major disaster, and the second approach is too expensive. Hence, the design philosophy should lie somewhere in between these two extremes.

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Earthquake-Resistant Buildings

The engineers do not attempt to make *earthquake-proof buildings* that *will not* get damaged even during the rare but strong earthquake; such buildings will be too robust and also too expensive. Instead, the engineering intention is to make buildings *earthquake-resistant*; such buildings resist the effects of ground shaking, although they may get damaged severely but would not collapse during the strong earthquake. Thus, safety of people and contents is assured in earthquake-resistant buildings, and thereby a disaster is avoided. This is a major objective of seismic design codes throughout the world.

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Earthquake Design Philosophy

(a) Under minor but frequent shaking, the main members of the building that carry vertical and horizontal forces should not be damaged; however building parts that do not carry load may sustain repairable damage.

(b) Under moderate but occasional shaking, the main members may sustain repairable damage, while the other parts of the building may be damaged such that they may even have to be replaced after the earthquake; and

(c) Under strong but rare shaking, the main members may sustain severe (even irreparable) damage, but the building should not collapse.

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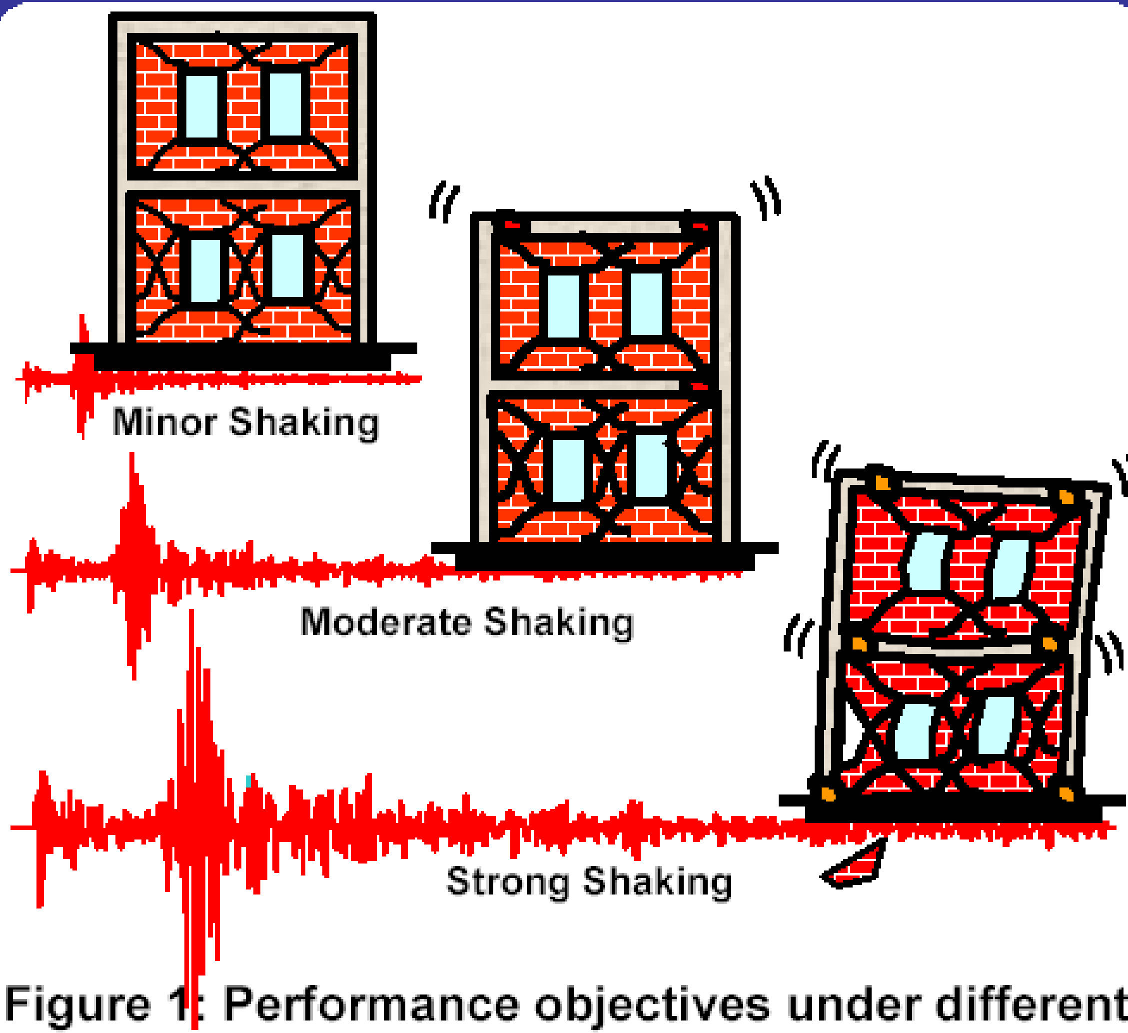

Figure 1: Performance objectives under different intensities of earthquake shaking – *seeking low repairable damage under minor shaking and collapse-prevention under strong shaking.*

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Thus, after minor shaking, the building will be fully operational within a short time and the repair costs will be small. And, after moderate shaking, the building will be operational once the repair and strengthening of the damaged main members is completed. But, after a strong earthquake, the building may become dysfunctional for further use, but will stand so that people can be evacuated and property recovered.

The consequences of damage have to be kept in view in the design philosophy. For example, important buildings, like hospitals and fire stations, play a critical role in post-earthquake activities and must remain functional immediately after the earthquake. These structures must sustain very little damage and should be designed for a higher level of earthquake protection. Collapse of dams during earthquakes can cause flooding in the downstream reaches, which itself can be a secondary disaster. Therefore, dams (and similarly, nuclear power plants) should be designed for still higher level of earthquake motion.

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Damage in Buildings: Unavoidable

Design of buildings to resist earthquakes involves *controlling the damage to acceptable levels at a reasonable cost*. Contrary to the common thinking that any crack in the building after an earthquake means the building is unsafe for habitation, engineers designing earthquake-resistant buildings recognize that some

during earthquakes. Some of these cracks *are* acceptable (in terms of both their *size* and *location*), while others *are not*. For instance, in a reinforced concrete frame building with masonry filler walls between columns, the cracks between vertical columns and masonry filler walls are acceptable, but diagonal cracks running through the columns are not (Figure 2).

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Figure 2: Diagonal cracks in columns jeopardize vertical load carrying capacity of buildings - *unacceptable damage*.

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Earthquake-resistant design is therefore concerned about ensuring that the damages in buildings during earthquakes are of the *acceptable* variety, and also that they occur at the right places and in right amounts. This approach of earthquake-resistant design is much like the use of electrical fuses in houses: *to protect the entire electrical wiring and appliances in the house, you sacrifice some small parts of the electrical circuit, called fuses; these fuses are easily replaced after the electrical over-current*. Likewise, to save the building from collapsing, you need to allow some pre-determined parts to undergo the acceptable type and level of damage.

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Acceptable Damage: Ductility

So, the task now is to identify acceptable forms of damage and desirable building behaviour during earthquakes. To do this, let us first understand how different materials behave. Consider *white chalk* used to write on blackboards and *steel pins* with solid heads used to hold sheets of paper together. Yes… a chalk *breaks easily*!! On the contrary, a steel pin *allows it to be bent back-and-forth*. Engineers define the property that allows steel pins to bend back-and-forth by large amounts, as *ductility*; chalk is a *brittle* material.

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So, the task now is to identify acceptable forms of damage and desirable building behaviour during earthquakes. To do this, let us first understand how different materials behave. Consider *white chalk* used to write on blackboards and *steel pins* with solid heads used to hold sheets of paper together. Yes... a chalk *breaks easily*!! On the contrary, a steel pin *allows it to be bent back-and-forth*. Engineers define the property that allows steel pins to bend back-and-forth by large amounts, as *ductility*; chalk is a *brittle* material.

factors affecting the building performance. Thus, earthquake-resistant design strives to predetermine the locations where damage takes place and then to provide good detailing at these locations to ensure ductile behaviour of the building.

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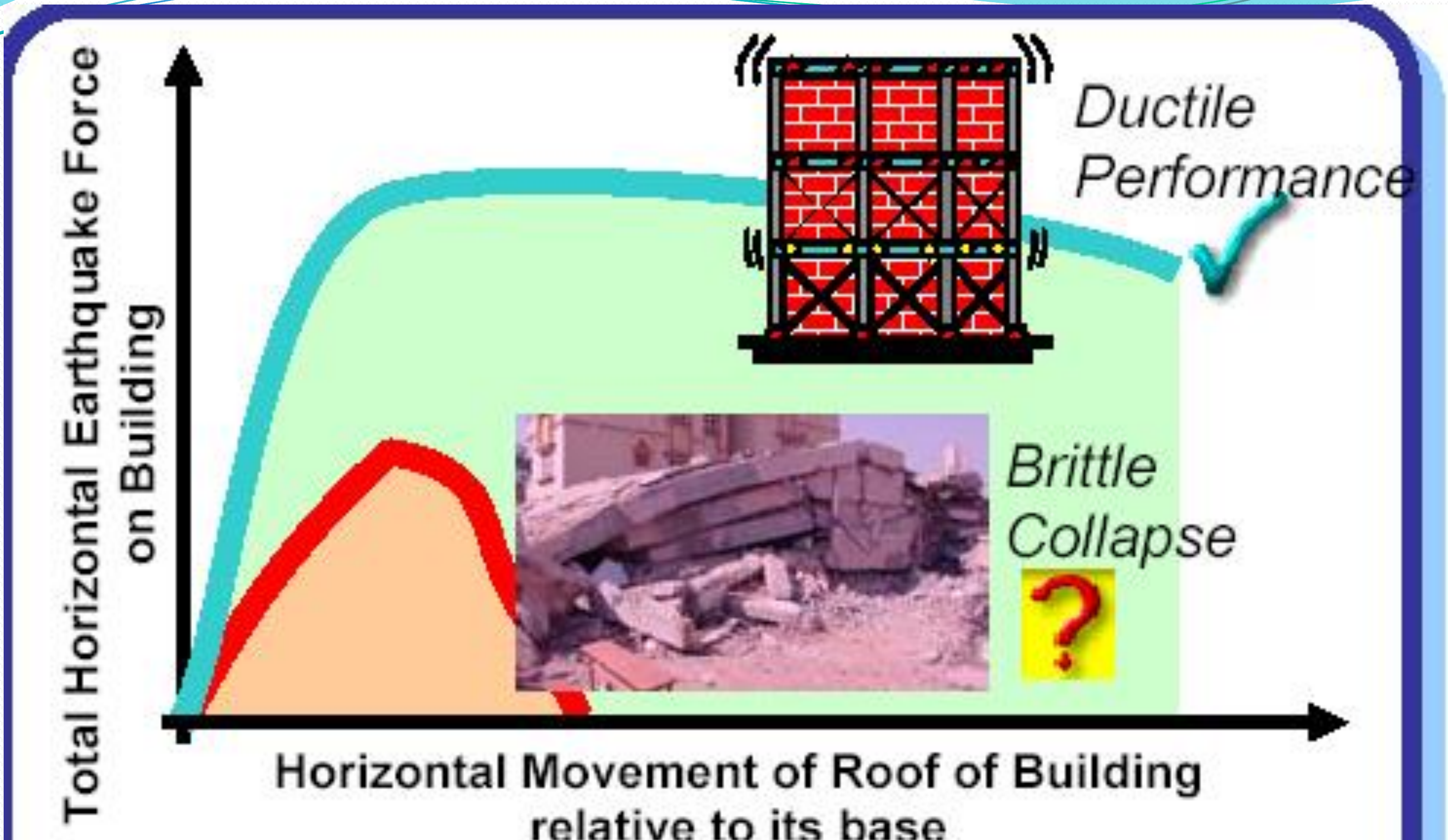

(a) **Building performances during earthquakes: two extremes** – *the ductile and the brittle.*

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Photo from: Housner & Jennings, *Earthquake Design Criteria*, EERI, USA

(b) Brittle failure of a reinforced concrete column

Figure 3: Ductile and brittle structures – *seismic design attempts to avoid structures of the latter kind.*

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9 How to Make Buildings Ductile for Good Seismic Performance?

Construction Materials

In India, most non-urban buildings are made in masonry. In the plains, masonry is generally made of burnt clay bricks and cement mortar. However, in hilly areas, stone masonry with mud mortar is more prevalent; but, in recent times, it is being replaced with cement mortar. Masonry can carry loads that cause *compression* (*i.e.*, pressing together), but can hardly take load that causes *tension* (*i.e.*, pulling apart) (Figure 1).

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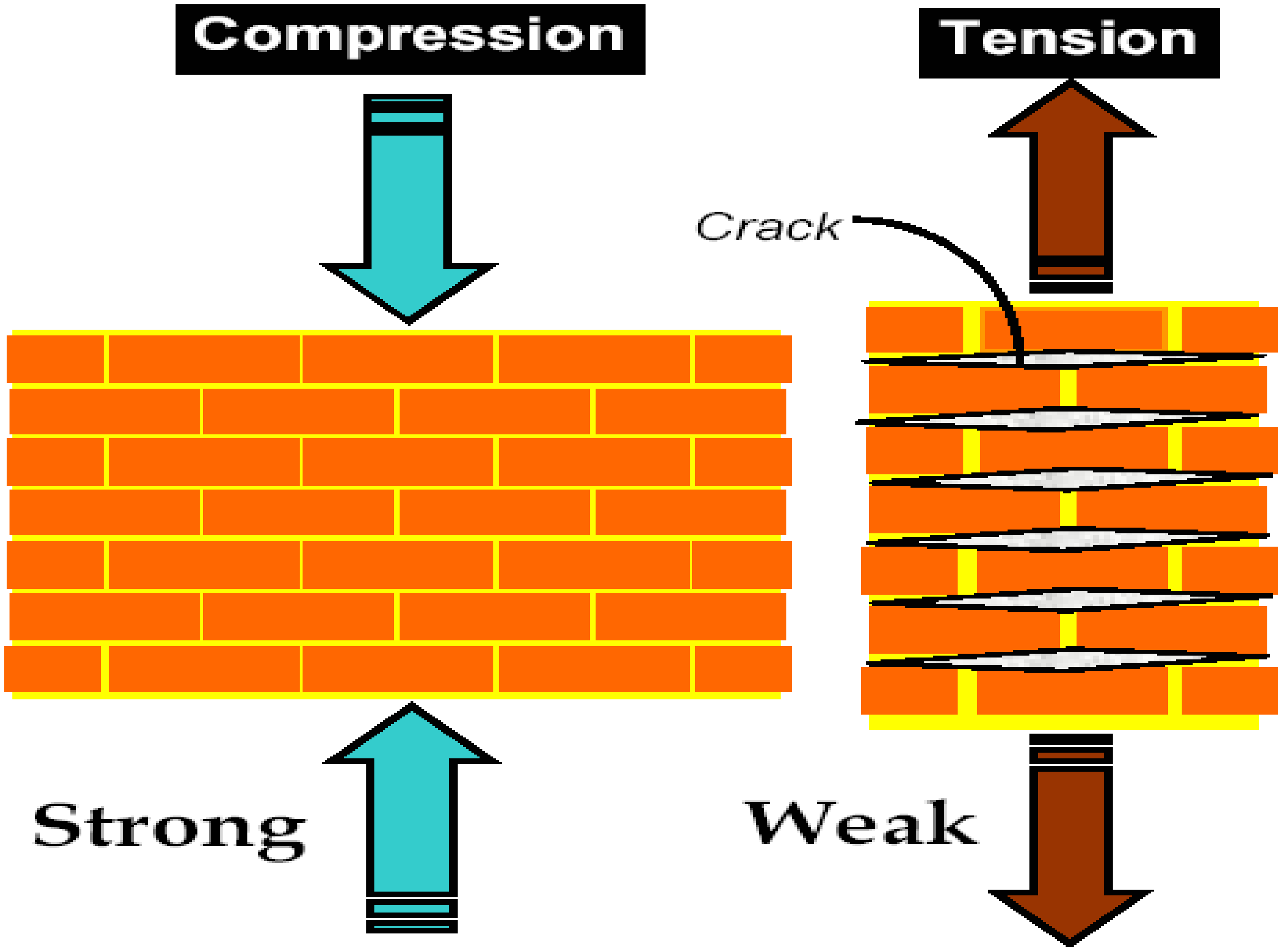

Figure 1: Masonry is strong in compression but weak in tension.

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Concrete is another material that has been popularly used in building construction particularly over the last four decades. Cement concrete is made of crushed stone pieces (called *aggregate*), sand, cement and water mixed in appropriate proportions. Concrete is much stronger than masonry under *compressive* loads, but again its behaviour in tension is poor. The properties of concrete critically depend on the amount of water used in making concrete; too much and too little water, both can cause havoc. In general, both masonry and concrete are brittle, and fail suddenly.

Steel is used in masonry and concrete buildings as reinforcement bars of diameter ranging from 6mm to 40mm. Reinforcing steel can carry both tensile and compressive loads. Moreover, steel is a *ductile material*. This important property of ductility enables steel bars to undergo large elongation before breaking.

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Concrete is used in buildings along with steel reinforcement bars. This composite material is called *reinforced cement concrete* or simply *reinforced concrete* (RC). The amount and location of steel in a member should be such that the failure of the member is by steel reaching its strength in tension before concrete reaches its strength in compression. This type of failure is *ductile failure*, and hence is preferred over a failure where concrete fails first in compression. Therefore, contrary to common thinking, providing too much steel in RC buildings can be harmful even!!

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Capacity Design Concept

Let us take two bars of same length and cross-sectional area - one made of a ductile material and another of a brittle material. Now, pull these two bars until they break!! You will notice that the ductile bar elongates by a large amount before it breaks, while the brittle bar breaks suddenly on reaching its maximum strength at a relatively small elongation (Figure 2). Amongst the materials used in building construction, steel is *ductile*, while masonry and concrete are *brittle*.

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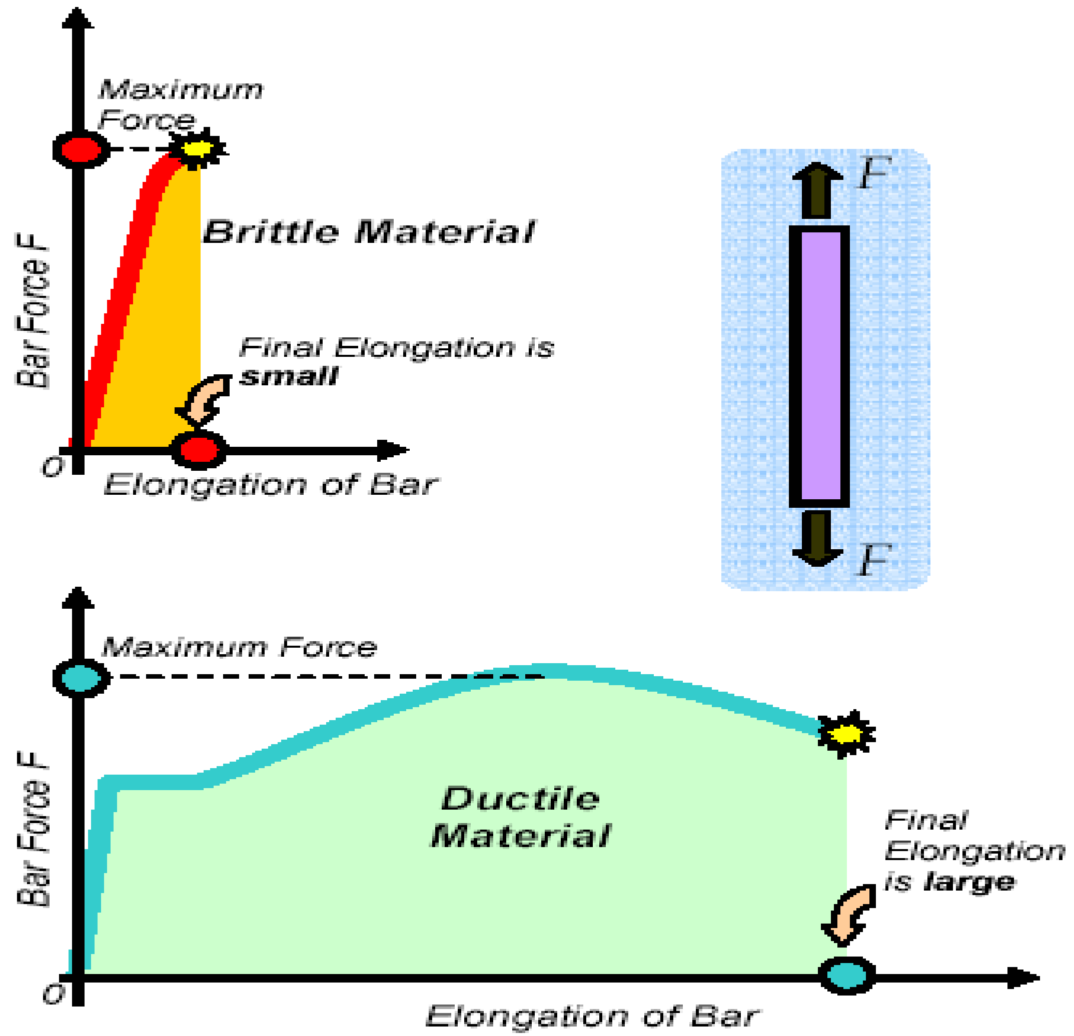

Figure 2: Tension Test on Materials – *ductile versus brittle materials.*

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Now, let us make a chain with links made of *brittle* and *ductile* materials (Figure 3). Each of these links will fail just like the bars shown in Figure 2. Now, hold the last link at either end of the chain and apply a force *F*. Since the same force *F* is being transferred through all the links, the force in each link is the same, *i.e.*, *F*. As more and more force is applied, eventually the chain will break when the *weakest link* in it breaks. If the ductile link is the *weak* one (*i.e.*, its capacity to take load is less), then the chain will show large final elongation. Instead, if the brittle link is the weak one, then the chain will fail suddenly and show small final elongation. Therefore, if we want to have such a *ductile* chain, we have to make the ductile link to be the *weakest* link.

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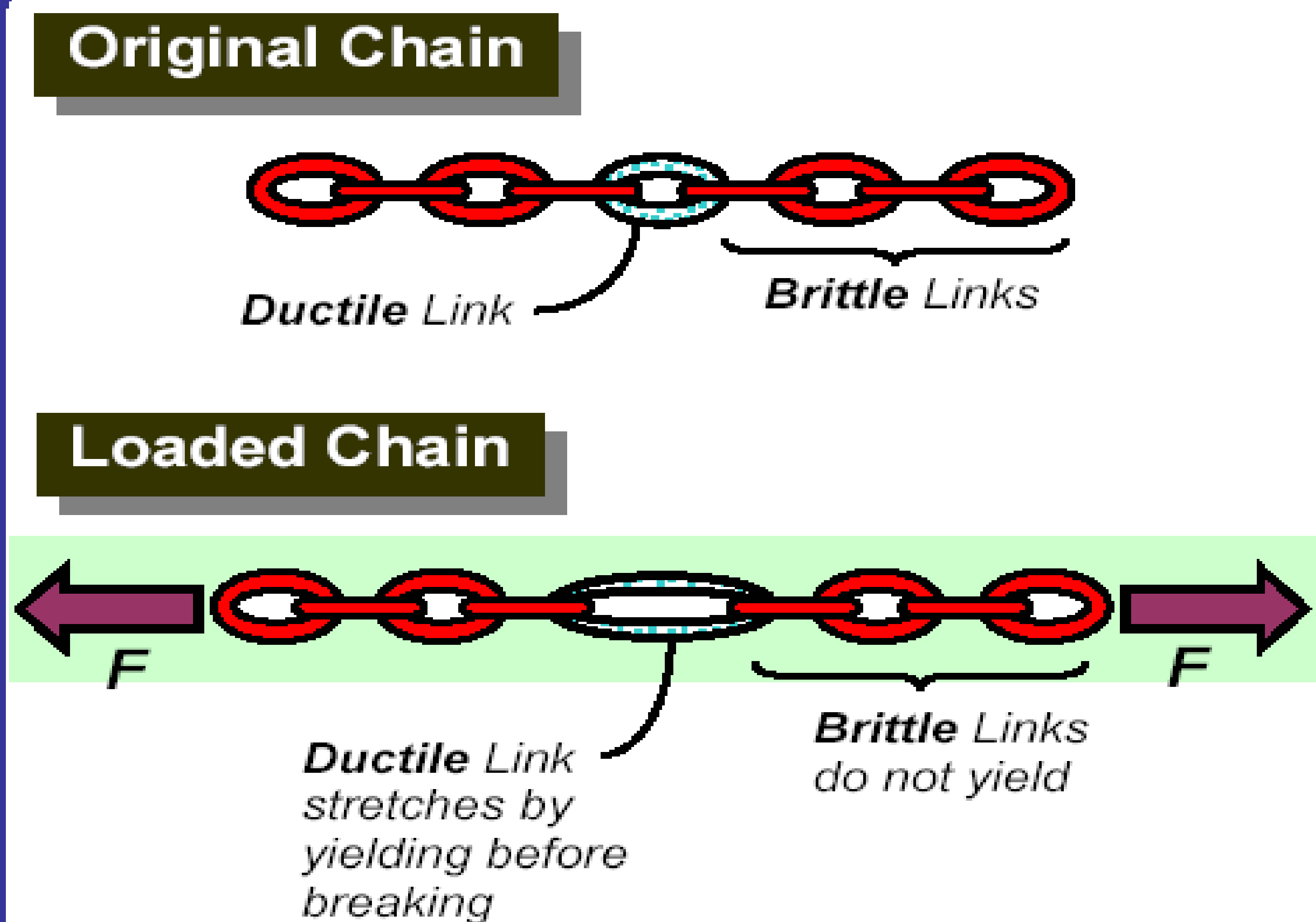

Figure 3: Ductile chain design.

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Buildings should be designed like the ductile chain. For example, consider the common urban residential apartment construction - the multi-storey building made of reinforced concrete. It consists of horizontal and vertical members, namely *beams* and *columns*. The seismic inertia forces generated at its floor levels are transferred through the various *beams* and *columns* to the ground. The correct building components need to be made ductile. The failure of a column can affect the stability of the whole building, but the failure of a beam causes localized effect. Therefore, it is better to make *beams* to be the ductile weak links than *columns*. This method of designing RC buildings is called the *strong-column weak-beam* design method (Figure 4).

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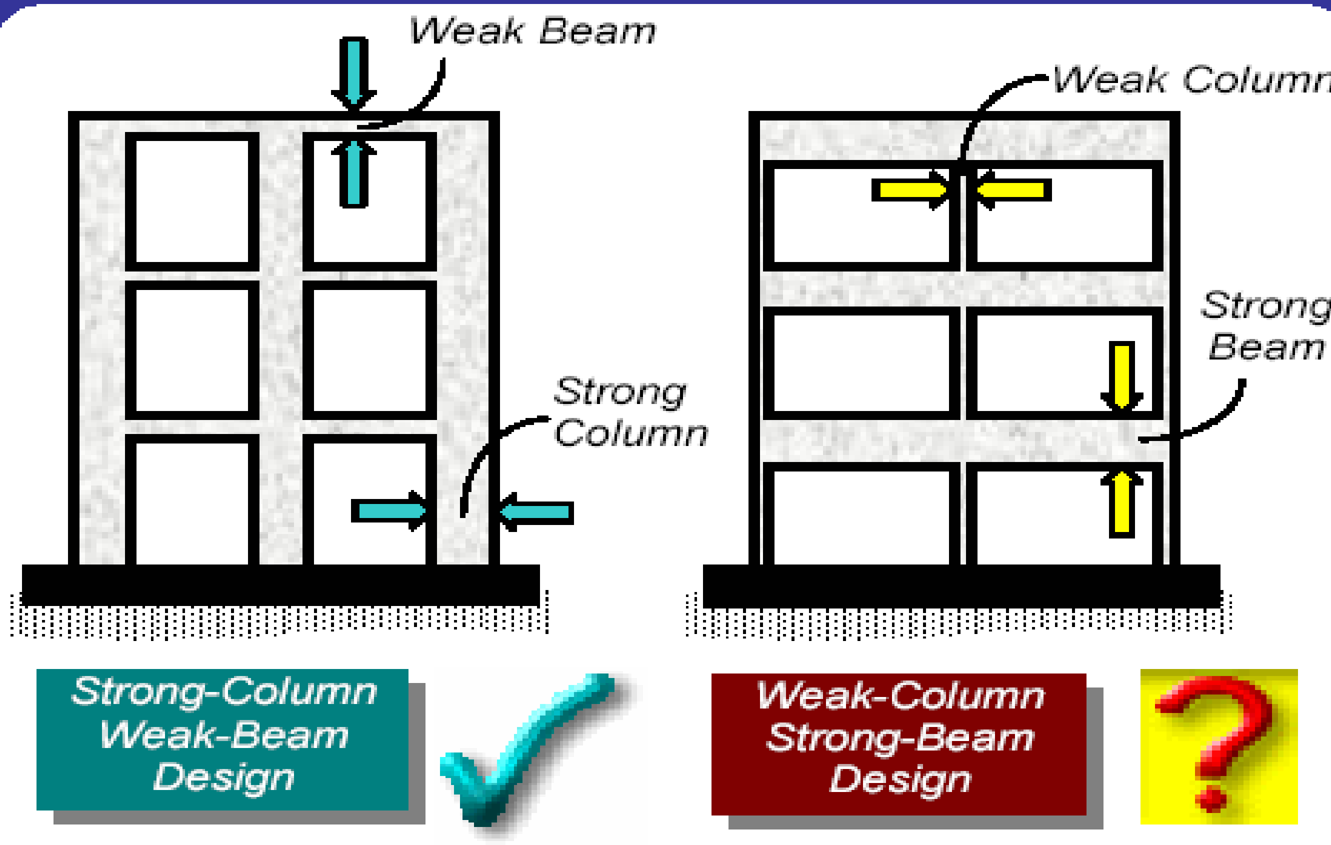

Figure 4: Reinforced Concrete Building Design: *the beams must be the weakest links and not the columns – this can be achieved by appropriately sizing the members and providing correct amount of steel reinforcement in them.*

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By using the *routine* design codes (meant for design against non-earthquake effects), designers may not be able to achieve a ductile structure. Special design provisions are required to help designers improve the ductility of the structure. Such provisions are usually put together in the form of a special *seismic* design code, *e.g.*, IS:13920-1993 for RC structures. These codes also ensure that adequate ductility is provided in the members where damage is expected.

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Quality Control in Construction

The capacity design concept in earthquake-resistant design of buildings will fail if the strengths of the brittle links fall below their minimum assured values. The strength of brittle construction materials, like masonry and concrete, is highly sensitive to the quality of construction materials, workmanship, supervision, and construction methods. Similarly, special care is needed in construction to ensure that the elements meant to be ductile are indeed provided with features that give adequate ductility. Thus, strict adherence to prescribed standards of construction materials and construction processes is essential in assuring an earthquake-resistant building. Regular testing of construction materials at qualified laboratories (at site or away), periodic training of workmen at professional training houses, and on-site evaluation of the technical work are elements of good quality control.

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10 How Flexibility of Buildings Affects their Earthquake Response?

Oscillations of Flexible Buildings

When the ground shakes, the base of a building moves with the ground, and the building swings back-and-forth. If the building were rigid, then every point in it would move by the same amount as the ground. But, most buildings are flexible, and different parts move back-and-forth by different amounts.

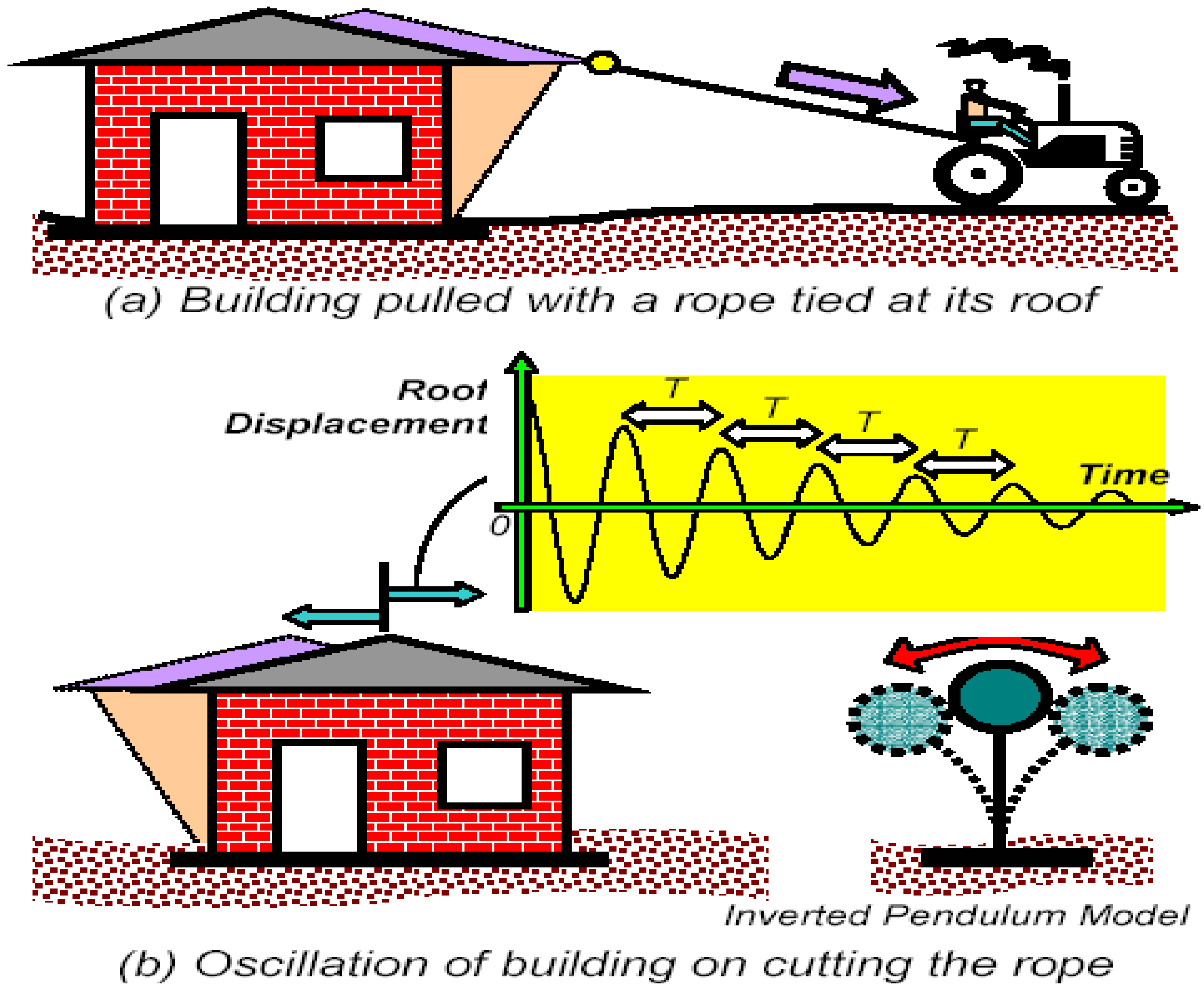

Figure 1: Free vibration response of a building:
the back-and-forth motion is periodic.

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Take a fat coir rope and tie one end of it to the roof of a building and its other end to a motorized vehicle (say a tractor). Next, start the tractor and pull the building; it will move in the direction of pull (Figure 1a). For the same amount of pull force, the movement is larger for a more flexible building. Now, cut the rope! The building will oscillate back-and-forth horizontally and after some time come back to the original position (Figure 1b); these oscillations are periodic. The time taken (*in seconds*) for each complete cycle of oscillation (*i.e.*, one complete *back-and-forth* motion) is the same and is called *Fundamental Natural Period T* of the building. Value of *T* depends on the building flexibility and mass; more the flexibility, the longer is the *T*, and more the mass, the longer is the *T*. In general, taller buildings are more flexible and have larger mass, and therefore have a longer *T*. On the contrary, low- to medium-rise buildings generally have shorter T (less than 0.4 sec).

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Fundamental natural period T is an inherent property of a building. Any alterations made to the building will change its T. Fundamental natural periods T of normal single storey to *20* storey buildings are usually in the range *0.05-2.00 sec*. Some examples of natural periods of different structures are shown in Figure 2.

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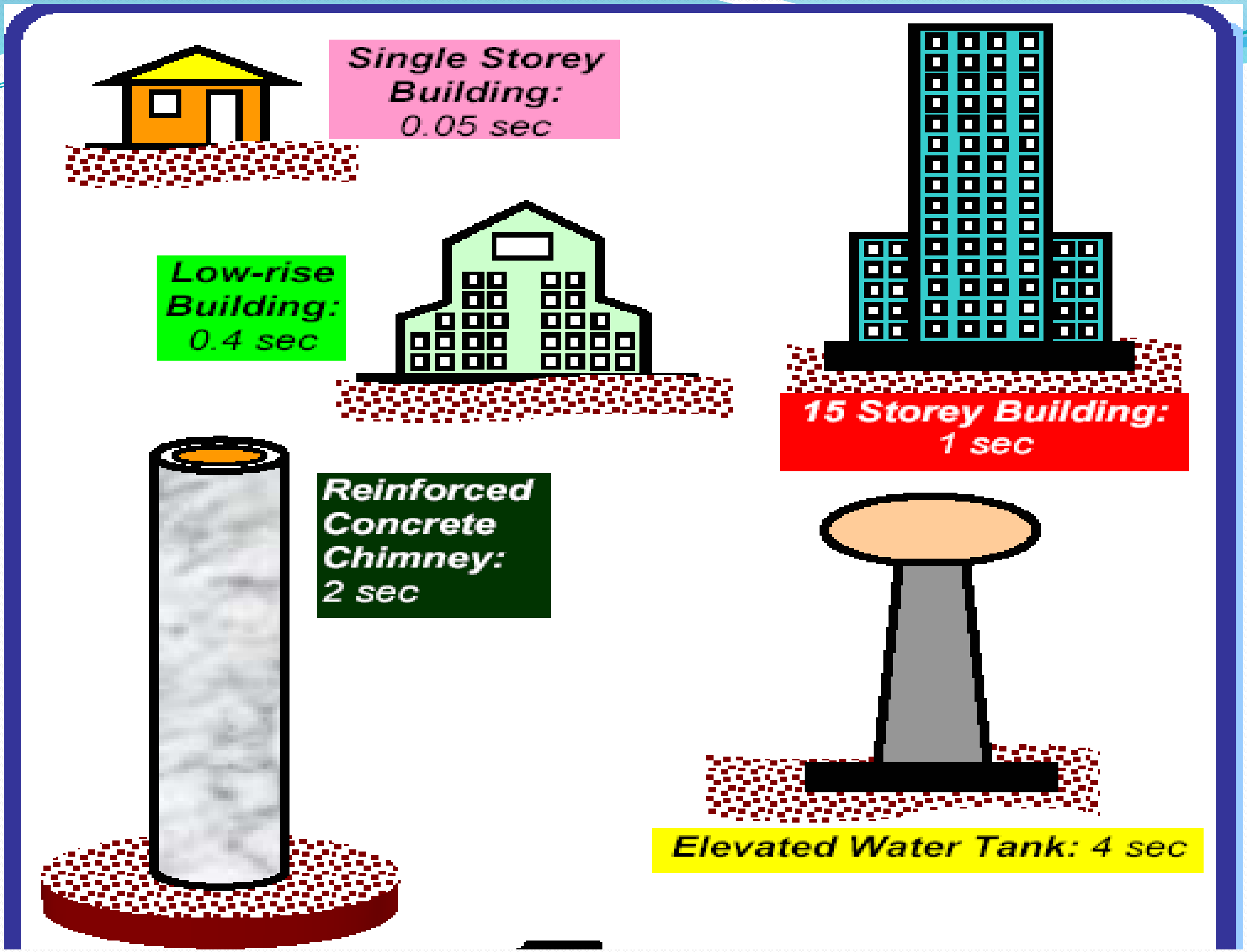

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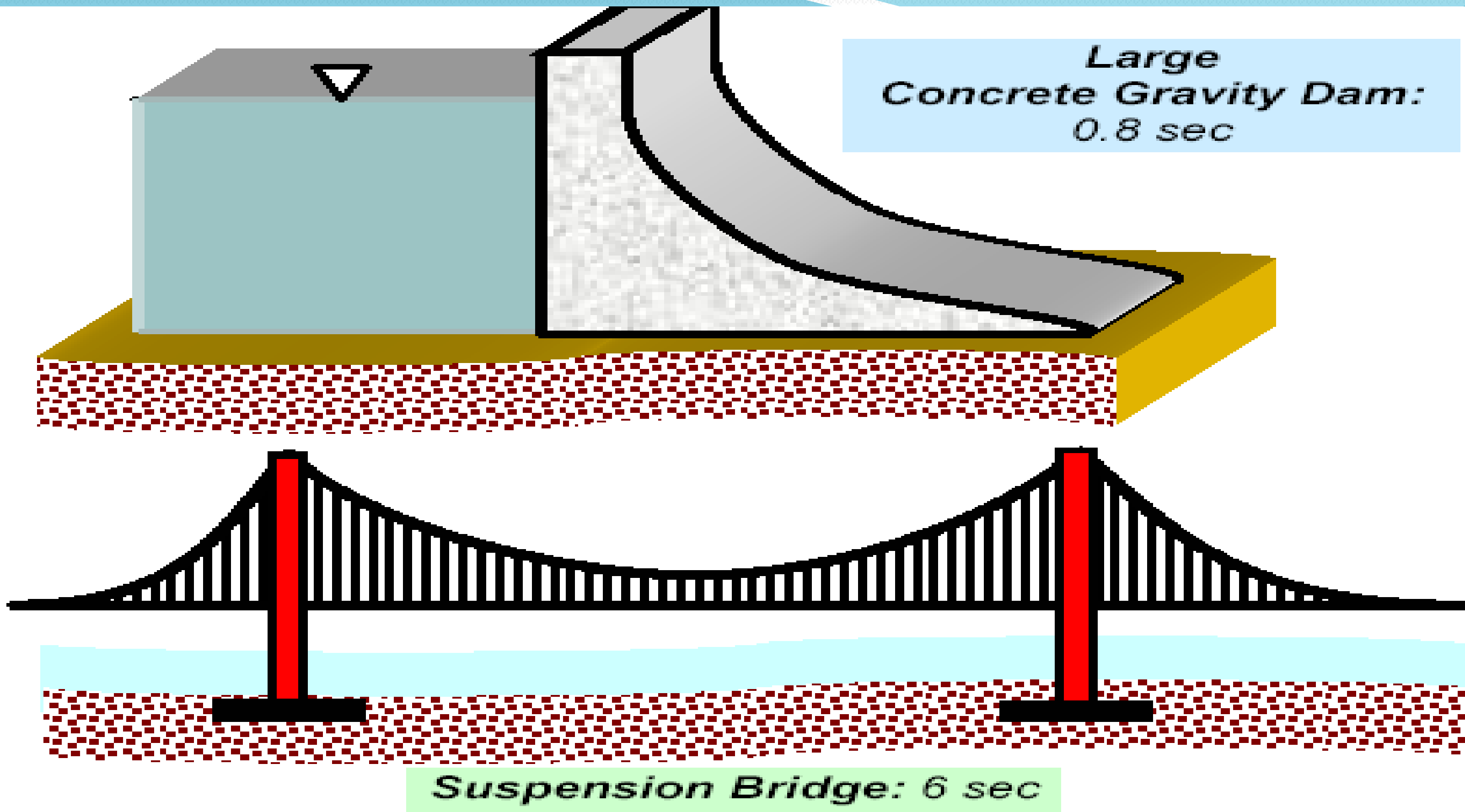

Adapted from: **Newmark, (1970),** *Current trends in the Seismic Analysis and Design of High Rise Structures*, **Chapter 16, in Wiegel, (1970),** *Earthquake Engineering*, **Prentice Hall, USA.**

Figure 2: Fundamental natural periods of structures differ over a large range. *The natural period values are only indicative; depending on actual properties of the structure, natural period may vary considerably.*

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Importance of Flexibility

The ground shaking during an earthquake contains a mixture of many sinusoidal waves of different frequencies, ranging from short to long periods (Figure 3). The time taken by the wave to complete one cycle of motion is called *period of the earthquake wave*. In general, earthquake shaking of the ground has waves whose periods vary in the range *0.03-33sec*. Even within this range, some earthquake waves are stronger than the others. Intensity of earthquake waves at a particular building location depends on a number of factors, including the *magnitude* of the earthquake, the *epicentral distance*, and the type of ground that the earthquake waves travelled through before reaching the location of interest.

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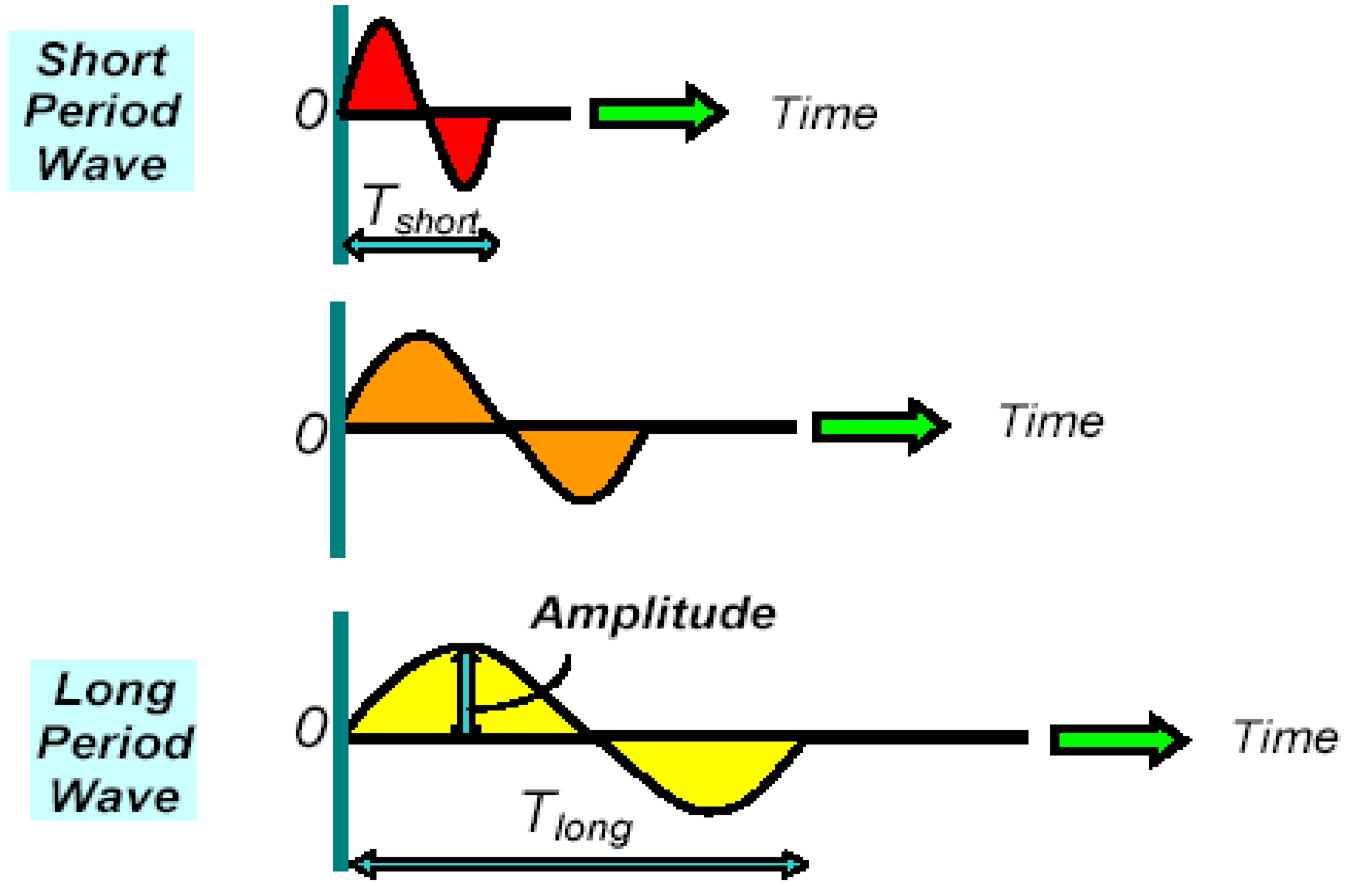

Figure 3: Strong Earthquake Ground Motion is transmitted by waves of different periods.

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In a typical city, there are buildings of many different sizes and shapes. One way of categorizing them is by their *fundamental natural period T*. The ground motion under these buildings varies across the city (Figure 4a). If the ground is shaken back-and-forth by earthquake waves that have short periods, then *short period buildings* will have large response. Similarly, if the earthquake ground motion has long period waves, then *long period buildings* will have larger response. Thus, depending on the value of *T* of the buildings and on the characteristics of earthquake ground motion (*i.e.*, the periods and amplitude of the earthquake waves), some buildings will be shaken more than the others.

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During the 1967 Caracas earthquake in South America, the response of buildings was found to depend on the thickness of soil under the buildings. Figure 4b shows that for buildings 3-5 storeys tall, the damage intensity was higher in areas with underlying soil cover of around 40-60m thick, but was minimal in areas with larger thickness of soil cover. On the other hand, the damage intensity was just the reverse in the case of 10-14 storey buildings; the damage intensity was more when the soil cover was in the range 150-300m, and small for lower thickness of soil cover. Here, the soil layer under the building plays the role of a filter, allowing some ground waves to pass through and filtering the rest.

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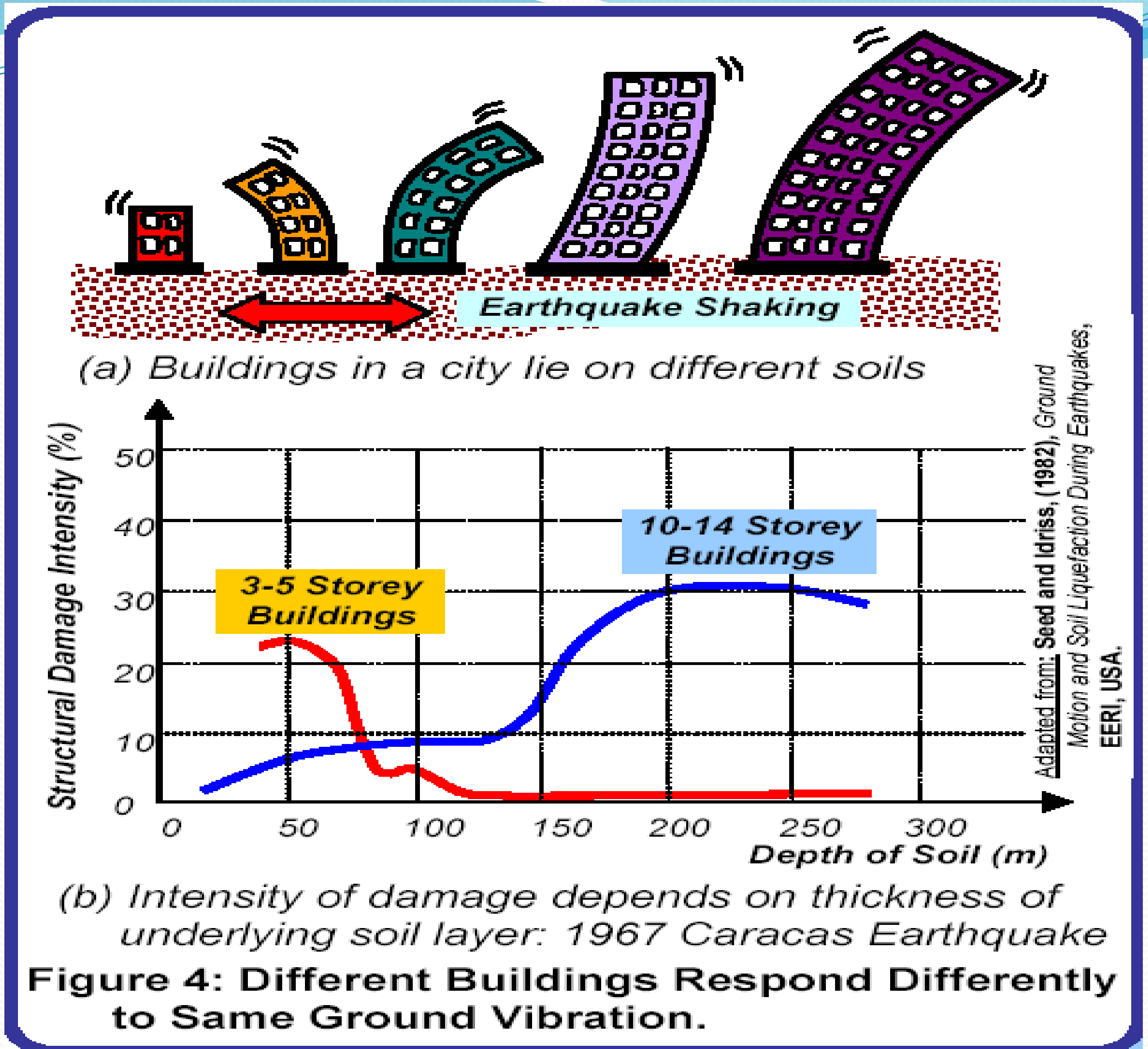

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Flexible buildings undergo larger relative horizontal displacements, which may result in damage to various nonstructural building components and the contents. For example, some items in buildings, like glass windows, cannot take large lateral movements, and are therefore damaged severely or crushed. Unsecured shelves might topple, especially at upper stories of multi-storey buildings. These damages may not affect safety of buildings, but may cause economic losses, injuries and panic among its residents.

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11 What are the Indian Seismic Codes?

Importance of Seismic Design Codes

Ground vibrations during earthquakes cause forces and deformations in structures. Structures need to be designed to withstand such forces and deformations. Seismic codes help to improve the behaviour of structures so that they may withstand the earthquake effects without significant loss of life and property. Countries around the world have procedures outlined in seismic codes to help design engineers in the planning, designing, detailing and constructing of structures. An earthquake-resistant building has four *virtues* in it, namely:

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(a) *Good Structural Configuration*: Its size, shape and structural system carrying loads are such that they ensure a direct and smooth flow of inertia forces to the ground.

(b) *Lateral Strength*: The maximum lateral (horizontal) force that it can resist is such that the damage induced in it does not result in collapse.

(c) *Adequate Stiffness*: Its lateral load resisting system is such that the earthquake-induced deformations in it do not damage its contents under low-to-moderate shaking.

(d) *Good Ductility*: Its capacity to undergo large deformations under severe earthquake shaking even after yielding, is improved by favourable design and detailing strategies.

Seismic codes cover all these aspects.

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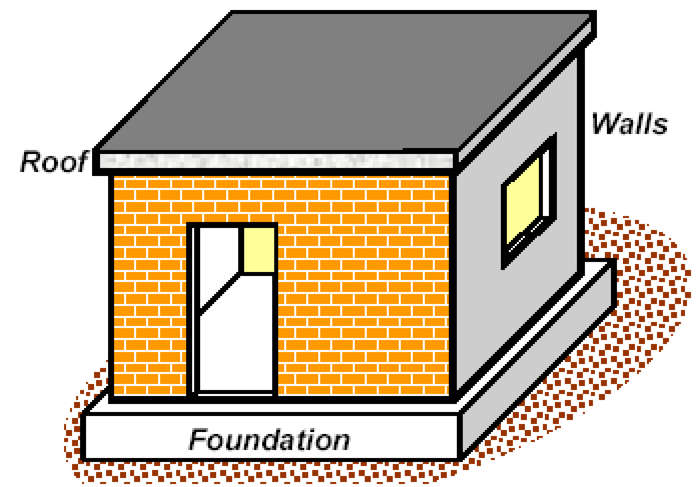
12 How do brick masonry houses behave during earthquakes?

Behaviour of Brick Masonry Walls

Masonry buildings are brittle structures and one of the most vulnerable of the entire building stock under strong earthquake shaking. The large number of human fatalities in such constructions during the past earthquakes in India corroborates this. Thus, it is very important to improve the seismic behaviour of masonry buildings. A number of earthquake-resistant features can be introduced to achieve this objective.



(a) Basic components of a masonry building

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Ground vibrations during earthquakes cause inertia forces at locations of mass in the building. These forces travel through the roof and walls to the foundation. The main emphasis is on ensuring that these forces reach the ground without causing major damage or collapse. Of the three components of a masonry building (*roof, wall* and *foundation*) (Figure 1a), the walls are most vulnerable to damage caused by horizontal forces due to earthquake. A wall topples down easily if pushed horizontally at the top in a direction perpendicular to its plane (termed *weak direction*), but offers much greater resistance if pushed along its length (termed *strong direction*) (Figure 1b).

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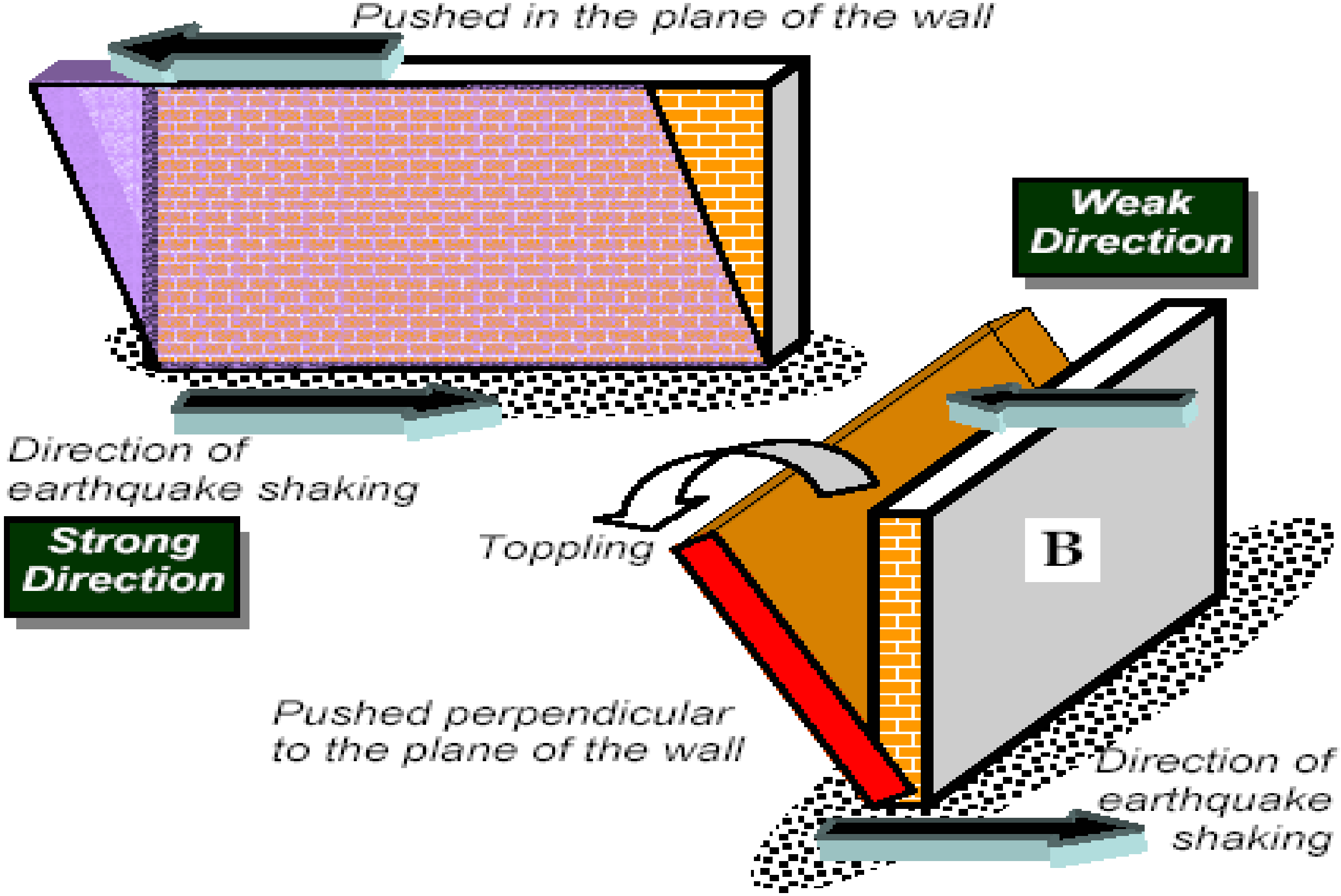

(b) Direction of force on a wall critically determines its earthquake performance

Figure 1: Basic components of a masonry building – *walls are sensitive to direction of earthquake forces.*

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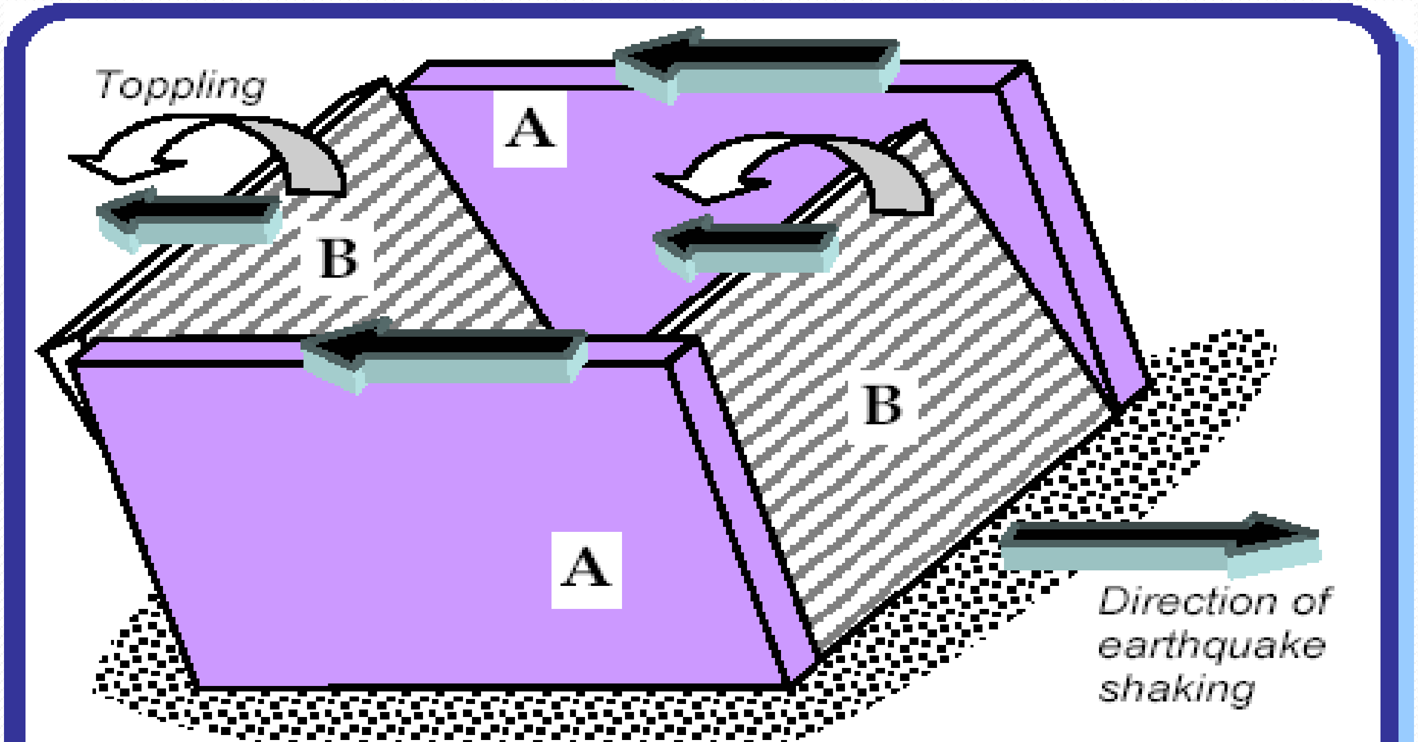
horizontal vibrations are the most damaging to normal masonry buildings. Horizontal inertia force developed at the roof transfers to the walls acting either in the weak or in the strong direction. If all the walls are not tied together like a box, the walls loaded in their weak direction tend to topple (Figure 2a).



(a) For the direction of earthquake shaking shown, wall B tends to fail

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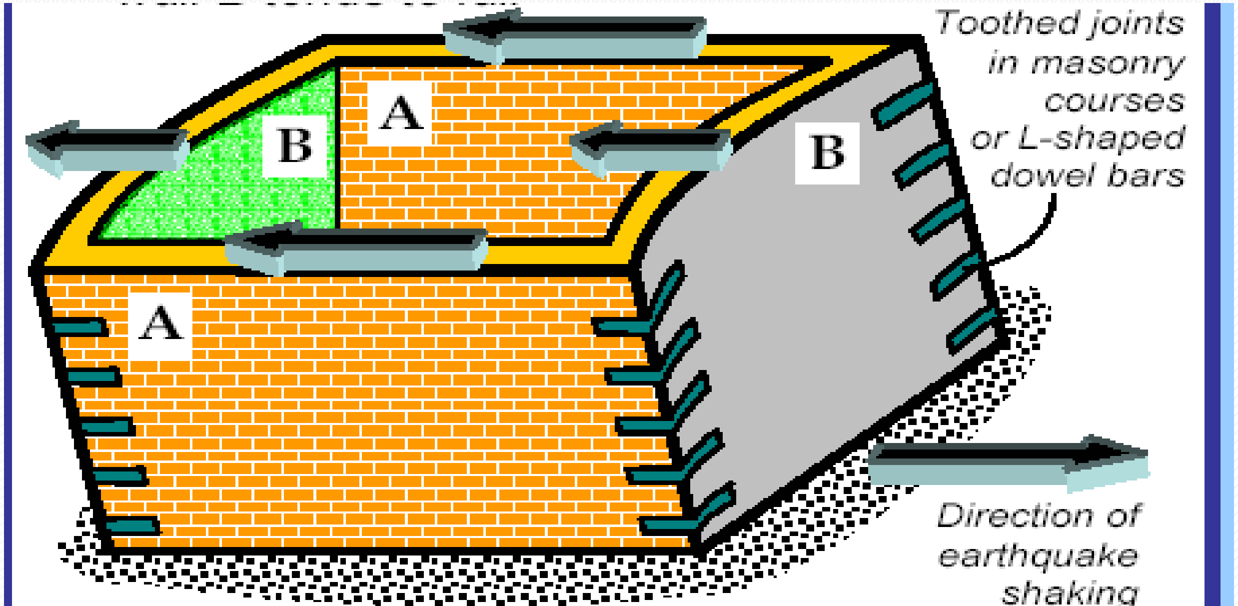
To ensure good seismic performance, all walls must be joined properly to the adjacent walls. In this way, walls loaded in their weak direction can *take advantage* of the good lateral resistance offered by walls loaded in their strong direction (Figure 2b). Further, walls also need to be tied to the roof and foundation to preserve their overall integrity.



(b) Wall B properly connected to Wall A (Note: roof is not shown): Walls A (loaded in strong direction) support Walls B (loaded in weak direction)

Figure 2: Advantage sharing between walls – *only possible if walls are well connected.*

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How to Improve Behaviour of Masonry Walls

Masonry walls are slender because of their small thickness compared to their height and length. A simple way of making these walls behave well during earthquake shaking is by making them act together as a box along with the roof at the top and with the foundation at the bottom. A number of construction aspects are required to ensure this box action. Firstly, connections between the walls should be good. This can be achieved by (a) ensuring good interlocking of the masonry courses at the junctions, and (b) employing horizontal bands at various levels, particularly at the lintel level. Secondly, the sizes of door and window openings need to be kept small. The smaller the openings, the larger is the resistance offered by the wall. Thirdly, the tendency of a wall to topple when pushed in the weak direction can be reduced by limiting its length-to-thickness and height-to-thickness ratios (Figure 3). Design codes specify limits for these ratios. A wall that is too tall or too long in comparison to its thickness, is particularly vulnerable to shaking in its weak direction (Figure 3).

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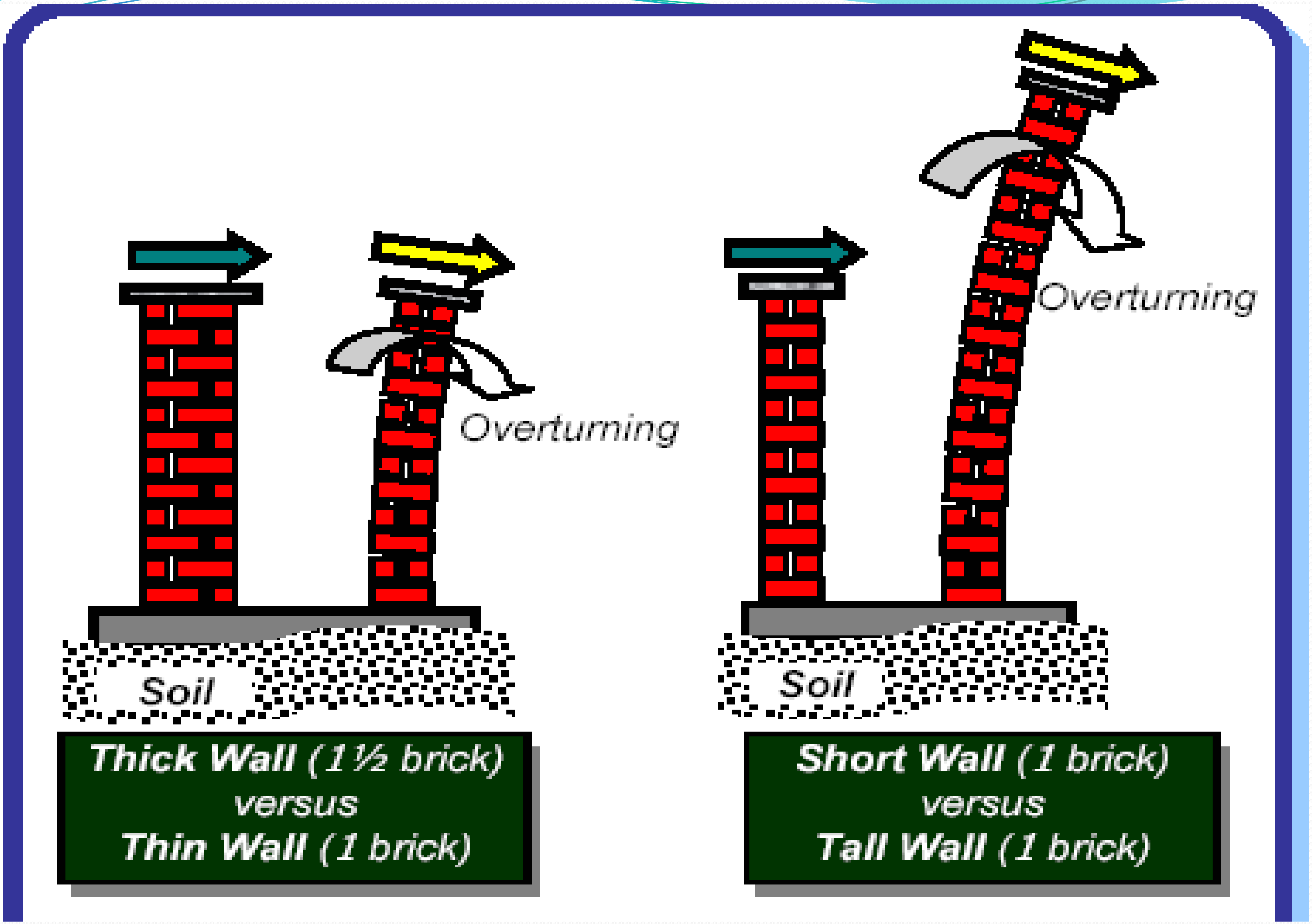

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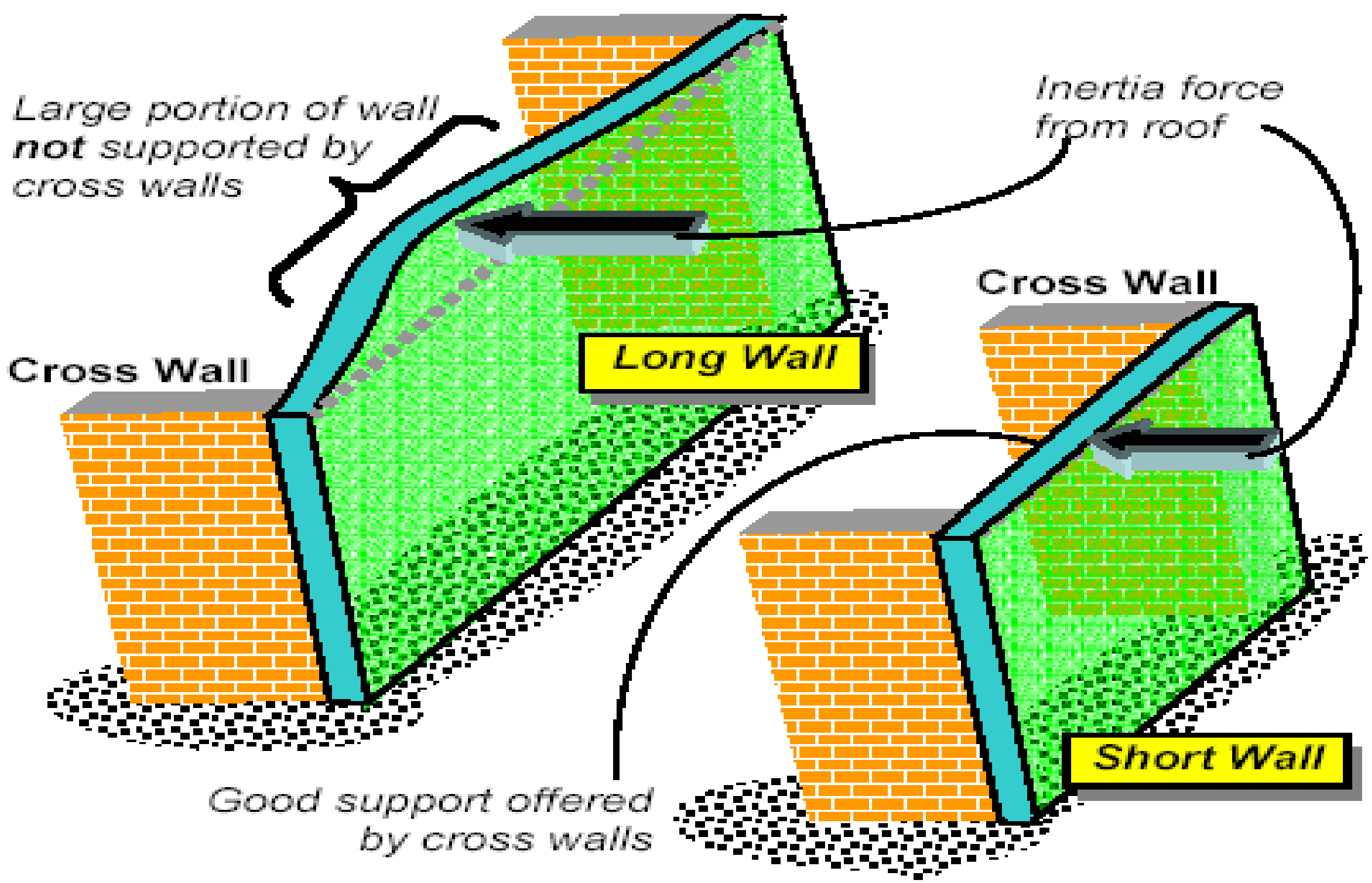

Figure 3: Slender walls are vulnerable – *height and length to be kept within limits. Note: In this figure, the effect of roof on walls is not shown.*

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Choice and Quality of Building Materials

materials and construction methods. A variety of masonry units are used in the country, *e.g.*, clay bricks (burnt and unburnt), concrete blocks (solid and hollow), stone blocks. *Burnt clay bricks* are most commonly used. These bricks are inherently porous, and so they absorb water. Excessive porosity is detrimental to good masonry behaviour because the bricks suck away water from the adjoining mortar, which results in poor bond between brick and mortar, and in difficulty in positioning masonry units. For this reason, bricks with low porosity are to be used, and they must be soaked in water before use to minimise the amount of water drawn away from the mortar.

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