“The Earth is held up by 4 elephants that stand on the back of a turtle. The turtle is balanced in turn on a cobra. When any of these animals moves, the Earth will tremble and shake.”
Science

An earthquake is a sudden, rapid shaking of the Earth caused by the release of strain energy stored in rocks.

Local Convective Currents

In the Mantle

~260 km of semi-molten mantle rises due to heat Sinks when temperature drops

Similar to movement you observe when you boil water in a clear glass pot

Crust is fractured

Convective movement acts as drag force on crustal plates:
- Causes separation where mantle is rising
- Causes collision where mantle is sinking
Earth's land masses about 200,000,000 years ago when there was one large land mass—Pangaea, or supercontinent.

Earth's land masses about 65,000,000 years ago when the supercontinent broke up into smaller continents.

Earth's land masses today, where India has collided with Eurasia. Eurasia continues to separate as the Atlantic Ocean widens.

Earth's land masses about 50,000,000 years into the future.
The Rings of Fire...

Elastic Rebound theory

- Elastic Strain Build-Up and Brittle Rupture

Stage A

Stage B

Stage C
Types of Inter-Plate Boundaries

- **Convergent Boundary**
- **Divergent Boundary**
- **Transform Boundary**
Indian Seismic Zone Map

Focus (Hypocenter)

• Point where motion first starts

Area/volume ruptured
Epicenter

- Projection of focus on ground

Focal Depth

- Depth of focus below ground
  - < 70 km  Shallow Focus EQs
  - 70 to 300 km  Intermediate Focus EQs
  - > 300 km  Deep Focus EQs
Epicentral Distance

• Distance of epicenter from point of interest on the Earth

Epicentral Distance

1° = 112 km

HYPOcentral Distance

• Direct distance from Focus to Station of interest
Foreshocks/Aftershocks

- Events of shaking before/after the main EQ event

Faults

- Planes along which slip takes place

Dip Slip Faults
- Normal
- Reverse

Strike Slip Faults
- Left Lateral
- Right Lateral
Seismic Waves

• Arrival at a site

![Diagram showing Seismic Waves, Surface Waves, Body Waves, Fault Rupture, Structure, Soil, and Geologic Strata.]

Seismic Waves...

• Body Waves

**P-Waves**
- Push and pull
- Extension
- Compression

**S-Waves**
- Up and down
- Side to side

![Diagram showing P-Waves and S-Waves with directions of energy transmission.]
• **Surface Waves**
  - *Love Waves*
    - Sideways in horizontal plane

  ![Love Waves Diagram](image1.png)

- **Rayleigh Waves**
  - Elliptic in vertical plane

  ![Rayleigh Waves Diagram](image2.png)

**Body Waves**...
Locating the Epicenter

- Different arrival times
  - \( P \)-waves: 1.5-8 km/sec
  - \( S \)-waves: 60-70% of \( P \)-waves (1-5 km/sec)

- Speeds may vary
  - Ratio between average speeds of \( P \) and \( S \) waves is quite constant!
  - Time-delay between arrival of \( P \)-and \( S \)-waves is used to estimate location of epicenter
Locating the Epicenter…

- **Estimates**
  - Arrival times of P and S waves
  - Wave velocities in the region

\[
\frac{V_P}{V_S} > 1
\]

\[
\therefore \Delta t = \frac{d}{V_S} - \frac{d}{V_P}
\]

\[
\therefore d = \frac{\Delta t}{\frac{1}{V_S} - \frac{1}{V_P}}
\]

**Approximate Distance (km) = \Delta t \times 8 \text{ km/s}!**
Locating the Epicenter…

- Can only “estimate” location

![Diagram showing three stations: Station 1, Station 2, and Station 3.]

Earthquake Magnitude

- Quantitative measure of physical shaking generated by the EQ
  - Size of the Earthquake

- Ways of measuring
  - Motion
  - Energy
Charles Richter (1935)
- used amplitude of body waves on seismograms to measure amount of energy released in an EQ

Earthquake Magnitude…

Richter Magnitude ($M_L$)

- Definition
  - $\log_{10}$ (Max. Amplitude in microns)
  - Wood-Anderson Seismograph
  - 100 km from Epicenter

- Measurement depends on
  - EQ size
  - Epicentral distance
  - Instrument type
• Scale is logarithmic

• No upper or lower limits
  – Can even be negative
  – Largest EQ recorded is 8.9!

• Correction for distance
  – so that it has a unique value for a given event
• **Weakness**
  – Does not depend on duration of shaking
  – Saturates with length of fault
  – Saturates with energy

• **2001 Bhuj EQ**
  – Magnitude 6.9 (IMD) versus 7.7 (USGS)

---

Many Magnitude Scales

• $M_L$: **Local Magnitude**
  – To describe local earthquakes within 500 km distance

• $M_b$: **Body or P-wave Magnitude**
  – Determined using P-wave amplitude

• $M_S$: **Surface-wave Magnitude**
  – Determined using Rayleigh wave amplitude of time period >20s
  – Commonly reported magnitude superseding $M_L$

• $M_w$: **Moment Magnitude**
  – Determined using rupture area, slip, and rock strength
  – More accurate measurement of energy released
  – Preferred by scientists
Many Magnitude Scales…

• Saturation of Magnitude Scales

![Graph showing magnitude scales](image)

Seismic Energy

• Amount of energy radiated by an EQ

• Energy released
  – About 30 times, if $M_L$ goes up by 1

• M4.0 EQ
  = Small nuclear weapon of 1000 ton yield!
### Global Occurrence of EQs

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Effects</th>
<th>Estimated Number per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0-3.0</td>
<td>Generally not felt but recorded</td>
<td>3 000 000</td>
</tr>
<tr>
<td>3.1-4.0</td>
<td>Often felt, but only minor damage</td>
<td>50 000</td>
</tr>
<tr>
<td>4.1-6.0</td>
<td>Slight damage to building</td>
<td>15 000</td>
</tr>
<tr>
<td>6.1-6.9</td>
<td>Can be destructive where people live in</td>
<td>120</td>
</tr>
<tr>
<td>7.0-7.9</td>
<td>Major earthquake; causes major damages</td>
<td>20</td>
</tr>
<tr>
<td>8.0 or greater</td>
<td>Great earthquake; Total destruction of nearby communities</td>
<td>1</td>
</tr>
</tbody>
</table>

#### Magnitude versus Intensity

- **Bright** (100 lumens)
- **Normal** (50 lumens)
- **Dull** (20 lumens)

100 Watt Bulb

**Intensity**

**Magnitude**
Magnitude versus Intensity…

- **Wattage**
  - is akin to EQ Magnitude

- **Brightness**
  - is akin to EQ Intensity

Earthquake intensity

- **Qualitative measure of strength of shaking manifested at a given place during the EQ**

  - **Influence of the Earthquake**

  - Before seismographs, Italian seismologist G. Mercalli and other European scientists classified earthquakes by the damage they produced qualitatively

  - Intensity Scale is a Roman numeral I-XII point scale to rate
    - Building damage
    - Ground movements
    - Human impact due to an earthquake
### Many Intensity scales

<table>
<thead>
<tr>
<th>Year</th>
<th>Scale Name</th>
<th>Formula</th>
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</thead>
<tbody>
<tr>
<td>1883</td>
<td>Rossi-Forel Scale</td>
<td>$I-X$</td>
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<tr>
<td></td>
<td>De-Rossi and Forel</td>
<td></td>
</tr>
<tr>
<td>1902</td>
<td>Mercalli Scale</td>
<td>$I-XII$</td>
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<tr>
<td></td>
<td>Mercalli</td>
<td></td>
</tr>
<tr>
<td>1931</td>
<td>Modified Mercalli Scale</td>
<td>$I-XII$</td>
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<tr>
<td></td>
<td>Wood and Neumann</td>
<td></td>
</tr>
<tr>
<td>1956</td>
<td>Modified Mercalli Scale</td>
<td>$I-XII$</td>
</tr>
<tr>
<td></td>
<td>(1956 Version)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Richter</td>
<td></td>
</tr>
<tr>
<td>1964</td>
<td>MSK Scale</td>
<td>$I-XII$</td>
</tr>
<tr>
<td></td>
<td>Medvedev, Sponheuer, Karnik</td>
<td></td>
</tr>
</tbody>
</table>

### Newer Scales

- **Not widely used yet**
  - 1998 European Macroseismic Scale $I-XII$
  - Japan Meteorological Agency Scale $1-7$
    - Used in Japan and Taiwan
  - Arabic Numerals!!!
Shortened Mercalli Scale

- I  Only instrument detect it
- II  People lying down feel it
- III  People on upper floors of building feel it, but may not know that it is earthquake
- IV  People indoors will probably feel it, but those outside may not.
- V   Nearly everyone feels it and wakes up even if sleeping.
- VI  Everyone feels the quake and it’s hard to walk.
- VII It is hard to stand.

Shortened mercalli scale...

- VIII People will not be able to drive cars. Poorly built buildings may fall. Chimneys may fall.
- IX  Most foundations are damaged. The ground cracks.
- X   Most buildings are destroyed. Water is thrown out of rivers and lakes.
- XI  Rails are bent. Bridges and underground pipelines are put out of service.
- XII Most things are leveled. Large objects may be thrown into the air.
isoseismals

• 2001 Bhuj Earthquake

MSK Intensity Scale (1964 Version)

• Russian Scientists
  – Medvedev, Sponheuer and Karnik

• Types of Structures (Buildings)
  – Structure A
    Buildings in field stone, rural structures, adobe houses, clay houses
  – Structure B
    Ordinary brick buildings, buildings of large block and prefabricated type, half timbered structures, buildings in natural hewn stone
  – Structure C
    Reinforced concrete buildings, well-built wooden structures
• Definition of quantity
  - Single, few : ~ 5%
  - Many : ~ 50%
  - Most: ~ 75%

• Classification of damage to buildings
  - Grade 1 : Sight damage
    • Fine cracks in plaster, fall of small pieces of plaster
  - Grade 2 : Moderate damage
    • Small cracks in walls, fall of fairly large piece of plaster, pantiles slip off, cracks in chimneys, parts of chimneys fall down
  - Grade 3 : Heavy damage
    • Large cracks in walls, fall of chimneys
  - Grade 4 : Destruction
    • Gaps in walls, parts of buildings may collapse, separate parts of the building lose their cohesion, inner walls collapse
  - Grade 5 : Total damage
    • Total collapse of buildings
• **Arrangement of the Scale**
  – Introductory letters are used in paragraphs throughout the scale as follows:
  (a) Persons and surroundings
  (b) Structures of all kinds
  (c) Nature

---

**MSK Intensity Scale**

I. **Not noticeable**
  (a) The intensity of vibrations is below the limit of sensibility; the tremor is detected and recorded by seismographs only.

II. **Scarcely noticeable (very slight)**
  (a) Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings.

III. **Weak, partially observed only**
  (a) The earthquake is felt indoors by a few people, outdoors only in favourable circumstances. The vibration is like that due to the passing of a light truck. Attentive observers notice a slight swinging of hanging objects.
IV. Largely observed

(a) The earthquake is felt indoors by a few people outdoors by few people. Here and there people awake, but no one is frightened. The vibration is like that due to the passing of a heavily loaded truck. Windows, doors, and dishes rattle. Floors and walls creak. Furniture begins to shake. Hanging objects swing slightly. Liquids in open vessels are slightly disturbed. In standing motor cars the shock is noticeable.

(b) 

(c) 

V. Awakening

(a) The earthquake is felt in doors by all, outdoors by many. Many sleeping people awake. A few run outdoors. Animals become uneasy. Buildings tremble throughout. Hanging objects swing. Pictures knock against walls or swing out of place. Occasionally pendulum clocks stop. Unstable objects may be overturned or shifted. Doors and windows are thrust open and slam back again. Liquids spill in small amounts from well-filled open containers. The sensation of vibration is like that due to a heavy object falling inside the building.

(b) 

(c) Slight waves on standing water; sometimes change in flow of springs.
VI. Frightening
(a) Felt by most indoors and outdoors. Many people in buildings are frightened and run outdoors. A few persons lose their balance. Domestic animals run out of their stalls. In many instances, dishes and glassware may break, books fall down, pictures move, and unstable objects overturn. Heavy furniture may possibly move and small steeple bells may ring.
(b) Damage of Grade 1 is sustained in single buildings of Type B and in many of Type A. Damage in some buildings of Type A is of Grade 2.
(c) Cracks up to widths of 1cm possible in wet ground; in mountains occasional landslips; change in flow of springs and in level of well-water.

VII. Damage to buildings
(a) Most people are frightened and run outdoors. Many find it difficult to stand. The vibration is noticed by persons driving motorcars. Large bells ring.
(b) In many buildings of Type C, damage of Grade 1 is caused; in buildings of Type B, damage is of Grade 2. Most buildings of Type A suffers damage of Grade 3, some of Grade 4. In single instances, landslips of roadway on steep slopes; cracks in roads; seams of pipelines damages; cracks in stone walls.
(c) Waves are formed on water, and is made turbid by mud stirred up. Water levels in wells change, and the flow of springs changes. Sometimes dry springs have their flow restored and existing springs stop flowing. In isolated instances, parts of sandy or gravelly banks slip off.
VIII. Destruction of buildings

(a) Fright and panic; also persons driving motor cars 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. Most buildings of Type A suffer damage of Grade 4. Many buildings of Type C suffer damage of Grade 4. Occasional breaking of pipe seams. Memorial and monuments move and twist. Tombstones overturn. Stone walls collapse.

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

IX. General damage to buildings

(a) General panic; considerable damage to furniture. Animals run to and fro in confusion, and cry.

(b) Many buildings of Type C suffer damage of Grade 3, and a few of Grade 4. Many buildings of Type B show a damage of Grade 2 and a few of Grade 5. Many buildings of Type A suffer damage of Grade 5. Monuments and columns fall. Considerable damage to reservoirs; underground pipes partly broken. In individual cases, railway lines are bent and roadway damaged.

(c) On flat and overflow of water, sand and mud is often observed. Ground cracks to widths of up to 10 cm, on slopes and river banks more than 10 cm. Furthermore, a large number of slight cracks in ground; falls of rock, many landslides and earth flows; large waves in water. Dry wells renew their flow and existing wells dry up.
X. General destruction of buildings

(a) Many buildings of Type C suffer damage of Grade 4, and a few of Grade 5. Many buildings of Type B show damage of Grade 5. Most of Type A have destruction of grade 5. Critical damage to dykes and dams. Severe damage to bridges. Railway lines are bent slightly. Underground pipes are bent or broken. Road paving and asphalt show waves.

(b) In ground, cracks up to widths of several centimeters, sometimes up to 1 meter. Parallel to water courses occur broad fissures. Loose ground slides from steep slopes. From river banks and steep coasts, considerable landslides are possible. In coastal areas, displacement of sand and mud; change of water level in wells; water from canals, lakes, rivers, etc., thrown on land. New lakes occur.

XI. Destruction

(a) Severe damage even to well-built buildings, bridges, water dams and railway lines. Highways become useless. Underground pipes destroyed.

(b) Ground considerably distorted by broad cracks and fissures, as well as movement in horizontal and vertical directions. Numerous landslips and falls of rocks. The intensity of the earthquake requires to be investigated specifically.
XII. Landscape changes

(a)

(b) Practically all structures above and below ground are greatly damaged or destroyed.

(c) The surface of the ground is radically changed. Considerable ground cracks with extensive vertical horizontal movements are observed. Falls of rock and slumping of river banks over wide areas, lakes are dammed; waterfalls appear, and rivers are deflected. The intensity of the earthquake requires to be investigated specially.

---

I versus PGA

- Peak Ground Accelerations (PGA)

<table>
<thead>
<tr>
<th>MMI</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>PGA (g)</td>
<td>0.03-0.04</td>
<td>0.06-0.07</td>
<td>0.10-0.15</td>
<td>0.25-0.30</td>
<td>0.50-0.55</td>
<td>&gt;0.60</td>
</tr>
</tbody>
</table>
Effect of distance

- Reduction with distance

1979 Imperial Valley

M~6.6 Earthquakes
**Magnitude versus I**

- Gutenberg and Richter, 1956

\[ M_L \approx (2/3)I_0 + 1 \]

- For using this equation, the Roman numbers of intensity are replaced with the corresponding Arabic numerals, e.g., intensity IX with 9.0

- Several other relations

---

**Tsunamis**

Meaning “waves in harbour”
Travelling 1000 km/hr can batter coast line with waves as high as 30 m, causing considerable damage
Liquefaction
Earthquake waves passing through certain wet soils, may cause it to lose its firmness and collapse.

Thank you...