Chapter 20: Causes of Earthquake

Introduction

Earthquakes are one of the most devastating natural phenomena, capable of causing widespread destruction and loss of life. For civil engineers, understanding the causes of earthquakes is fundamental to designing structures that can withstand seismic forces. This chapter explores in detail the geophysical, geological, and anthropogenic causes of earthquakes. A sound grasp of these causes is critical in assessing seismic risk and planning for resilient infrastructure.

20.1 Classification of Earthquakes Based on Causes

Earthquakes are classified based on their origin or causative factors. These include:

1. **Tectonic Earthquakes**
2. **Volcanic Earthquakes**
3. **Collapse Earthquakes**
4. **Explosion-induced Earthquakes**
5. **Reservoir-induced Earthquakes**
6. **Isostatic Adjustment Earthquakes**
7. **Induced Seismicity due to Human Activities**

20.2 Tectonic Earthquakes

20.2.1 Plate Tectonics Theory

Tectonic earthquakes are the most common and destructive type, caused by the movement of the Earth's lithospheric plates. The theory of plate tectonics explains that the lithosphere is divided into several major and minor plates that float over the semi-fluid asthenosphere. These plates interact at their boundaries, leading to stress accumulation and eventual release as seismic energy.

20.2.2 Types of Plate Boundaries

- **Convergent Boundaries:** Plates collide, causing compression. Example: Himalayas.
- **Divergent Boundaries:** Plates move apart, causing tension. Example: Mid-Atlantic Ridge.
- **Transform Boundaries:** Plates slide past each other. Example: San Andreas Fault.

20.2.3 Faulting and Elastic Rebound Theory

A fault is a fracture in the Earth's crust where blocks of rock move relative to each other. The **Elastic Rebound Theory** explains how stress builds up in rocks until it exceeds their strength, causing a sudden rupture and release of energy—an earthquake.

20.3 Volcanic Earthquakes

Volcanic earthquakes are associated with volcanic activity and occur due to:

- Movement of magma beneath the Earth's surface.
- Sudden fracturing of rocks due to pressure from magma.
- Collapse of volcanic structures.

These are typically localized but can be precursors to volcanic eruptions. They occur in regions known as volcanic belts.

20.4 Collapse Earthquakes

Collapse earthquakes are minor and occur due to:

- Collapse of underground caves or mine tunnels.
- Sudden failure of rock strata.
- Roof falls in mines or karst topography (limestone areas with sinkholes and caves).

These earthquakes are generally of low magnitude but may still affect localized infrastructure.

20.5 Explosion-induced Earthquakes

These are man-made earthquakes caused by:

- Nuclear detonations.
- Large-scale chemical explosions (e.g., mining operations or weapon testing).
- Construction activities involving heavy blasting.

They are usually of short duration and have a distinct seismic signature that differentiates them from natural quakes.

20.6 Reservoir-Induced Seismicity (RIS)

20.6.1 Concept of RIS

Reservoir-induced seismicity refers to earthquakes that occur due to the filling of large reservoirs behind dams. The weight of the water increases stress on underlying faults and can lubricate fault lines through water seepage.

20.6.2 Mechanism

- **Hydrostatic pressure** due to water impoundment increases normal and shear stress.
- Water infiltration increases pore pressure, reducing friction on faults.
- This can trigger slippage along pre-existing weak zones.

20.6.3 Notable Examples

- Koyna Dam, India (1967 earthquake, magnitude 6.3)
- Lake Mead, USA

20.7 Isostatic Adjustment Earthquakes

These earthquakes are caused by **isostatic rebound**, where land masses rise or fall due to removal or addition of surface loads such as glaciers, sediment deposits, or erosion.

- Common in post-glacial regions.
- As crust readjusts, it can cause deep-seated seismic events.

20.8 Induced Seismicity Due to Human Activities

Modern industrial and developmental activities also contribute to induced seismicity. These include:

20.8.1 Deep Well Injection

- Disposal of industrial fluids, wastewater, or CO_2 in deep wells can alter pore pressure and stress regimes.
- Documented cases in Oklahoma, USA, where seismicity increased significantly due to fracking and injection.

20.8.2 Hydraulic Fracturing (Fracking)

- High-pressure injection of fluid to fracture shale rocks.
- While microseismicity is expected, improper control can trigger larger seismic events.

20.8.3 Mining and Quarrying

- Blasting operations, excavation, and mine collapse can lead to small earthquakes.
- Long-term mining alters the stress field in the Earth's crust.

20.8.4 Geothermal and Oil Extraction

- Withdrawal of fluids can create voids or reduce subsurface pressure.
- Ground subsidence and fault reactivation may follow.

20.9 Seismic Gaps and Earthquake Prediction

20.9.1 Seismic Gaps

A **seismic gap** is a segment of an active fault known to produce significant earthquakes that has not slipped in an unusually long time. These are considered zones of accumulated strain and hence, future earthquake hotspots.

20.9.2 Earthquake Precursors

While exact prediction is still unreliable, some observed precursors include:

- Foreshocks
- Ground tilting or uplift
- Changes in groundwater levels

- Radon emission anomalies

20.10 Role of Geological Structures

20.10.1 Faults

- **Normal Faults:** Tensional stress – crust extends.
- **Reverse (Thrust) Faults:** Compressional stress – crust shortens.
- **Strike-Slip Faults:** Lateral motion – shear stress.

20.10.2 Folds, Joints, and Rock Strength

The geological setting, rock composition, and orientation of faults/folds significantly influence how and where seismic energy is stored and released.

20.11 Earthquake Belts and Zones

20.11.1 Circum-Pacific Belt (Ring of Fire)

- Most seismically active zone.
- Includes Japan, Indonesia, Chile, USA (West Coast).

20.11.2 Alpine-Himalayan Belt

- Includes Iran, Turkey, Northern India, Nepal.
- Caused by collision between Indian and Eurasian plates.

20.11.3 Mid-Oceanic Ridges

- Seismic activity along divergent boundaries under the ocean.

20.11.4 Intraplate Earthquakes

- Occur within a tectonic plate, away from boundaries.
- Example: Bhuj Earthquake (2001), India.

20.12 Earthquake Magnitude and Energy Release

20.12.1 Magnitude Scales

Magnitude represents the energy released at the source of the earthquake.

- **Richter Scale (ML):** Logarithmic scale introduced in 1935 by Charles Richter. Each increase by 1.0 unit represents a tenfold increase in amplitude and ~31.6 times more energy release.
- **Moment Magnitude Scale (Mw):** More accurate for large earthquakes, based on seismic moment (fault area × slip × rock rigidity).
- **Body Wave (Mb) and Surface Wave (Ms) Magnitudes:** Used for different types of waves but now largely replaced by Mw.

20.12.2 Energy Released by Earthquakes

The energy E (in joules) released by an earthquake is approximately calculated as:

$$\log E = 1.5\,M + 4.8$$

where M is the magnitude on the Richter scale.

20.13 Seismic Waves and Their Propagation

20.13.1 Types of Seismic Waves

- **Body Waves:**
    - **P-waves (Primary):** Longitudinal, compressional, fastest, travel through solids and liquids.
    - **S-waves (Secondary):** Transverse, shear, travel only through solids, slower than P-waves.
- **Surface Waves:**
    - **Love Waves:** Horizontal shear, damaging to foundations.
    - **Rayleigh Waves:** Rolling motion, both vertical and horizontal, cause most of the shaking.

20.13.2 Wave Propagation and Attenuation

- Seismic waves decrease in intensity with distance (attenuation).
- Wave speed and behavior change depending on rock type, water content, and layering.
- Amplification can occur in soft soils or sedimentary basins.

20.14 Depth of Focus

20.14.1 Classification Based on Focal Depth

- **Shallow Focus:** < 70 km depth; most destructive.
- **Intermediate Focus:** 70–300 km depth.
- **Deep Focus:** > 300 km; less surface shaking due to energy dispersion.

Shallow earthquakes are typically associated with subduction zones and transform faults.

20.15 Microseismicity and Background Seismic Noise

- **Microseismicity:** Small earthquakes (M < 2.0) that occur frequently but are generally not felt. Important for early warning systems and fault monitoring.
- **Seismic Noise:** Continuous vibrations caused by ocean waves, human activity, and atmospheric pressure variations. It must be filtered out during seismological data analysis.

20.16 Paleoseismology and Historical Seismicity

20.16.1 Paleoseismology

The study of prehistoric earthquakes by analyzing geological layers and faults.

- Uses trenching, radiocarbon dating, and stratigraphic correlation.
- Helps identify recurrence intervals of large earthquakes.

20.16.2 Historical Records

- Ancient texts, temple damage records, and archaeological evidence.
- Important in regions lacking modern seismic data (e.g., parts of India, China).

20.17 Triggering Mechanisms of Earthquakes

20.17.1 Natural Triggers

- Stress transfer from nearby earthquakes (Coulomb stress changes).
- Landslides or sudden sediment collapse underwater.

- Solar tidal forces (minor but measurable).

20.17.2 Anthropogenic Triggers

- Reservoir filling (as previously covered).
- Underground nuclear testing.
- Rapid urban construction altering ground stress distribution.

20.18 Earthquake Clustering and Swarm Activity

20.18.1 Aftershocks

- Smaller earthquakes following a mainshock.
- Can continue for weeks or months.
- Follow **Omori's Law**: frequency decreases with time.

20.18.2 Foreshocks

- Smaller quakes before a mainshock.
- May help identify stress buildup, but not always present.

20.18.3 Earthquake Swarms

- Numerous small-to-moderate earthquakes occurring over a short period without a single outstanding mainshock.
- Often volcanic or geothermal in origin.

20.19 Earthquake Cycle and Recurrence

20.19.1 Earthquake Cycle

A sequence of stress accumulation, release, and reaccumulation along faults.

Phases:

1. **Interseismic Phase:** Stress builds up slowly.
2. **Coseismic Phase:** Sudden release during the earthquake.
3. **Postseismic Phase:** Adjustment and aftershock period.

20.19.2 Recurrence Interval

The average time between significant earthquakes on a fault segment.

- Estimated using paleoseismic, historical, and instrumental data.
- Crucial for hazard assessment and zoning.

20.20 Influence of Geological and Geomorphological Features

- **Soil Amplification:** Soft clays and loose sands increase ground shaking.
- **Topographic Effects:** Hills, ridges, and valleys can modify seismic wave behavior.
- **Liquefaction Potential:** Saturated sandy soils may behave like a liquid during strong shaking.
