University of Baghdad
College of Engineering
Department of Mechanical Engineering

EARTHQUAKES

UNDERSTANDING, IMPACTS AND RESILIENT FUTURE

By
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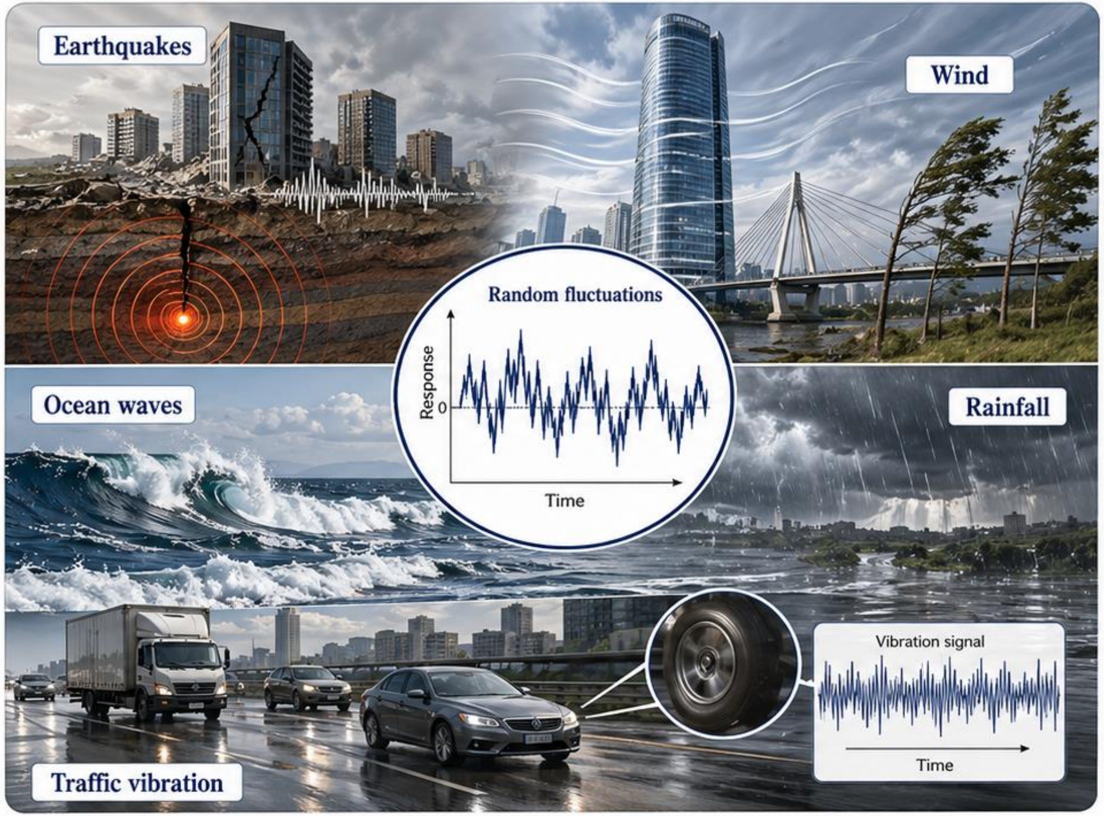
Presentation Outline

Random Phenomena and Earthquakes

From random phenomena to earthquake engineering applications.

Introduction to random phenomena



Definition

A random phenomenon is an event or process whose exact outcome cannot be predicted with certainty before it occurs. Although the behavior is uncertain, it can be studied using probability, statistics, and observations.

Main characteristics

- Uncertain occurrence or response
- Irregular variation with time or space
- Described statistically rather than exactly
- Affected by many complex factors

Examples and engineering importance

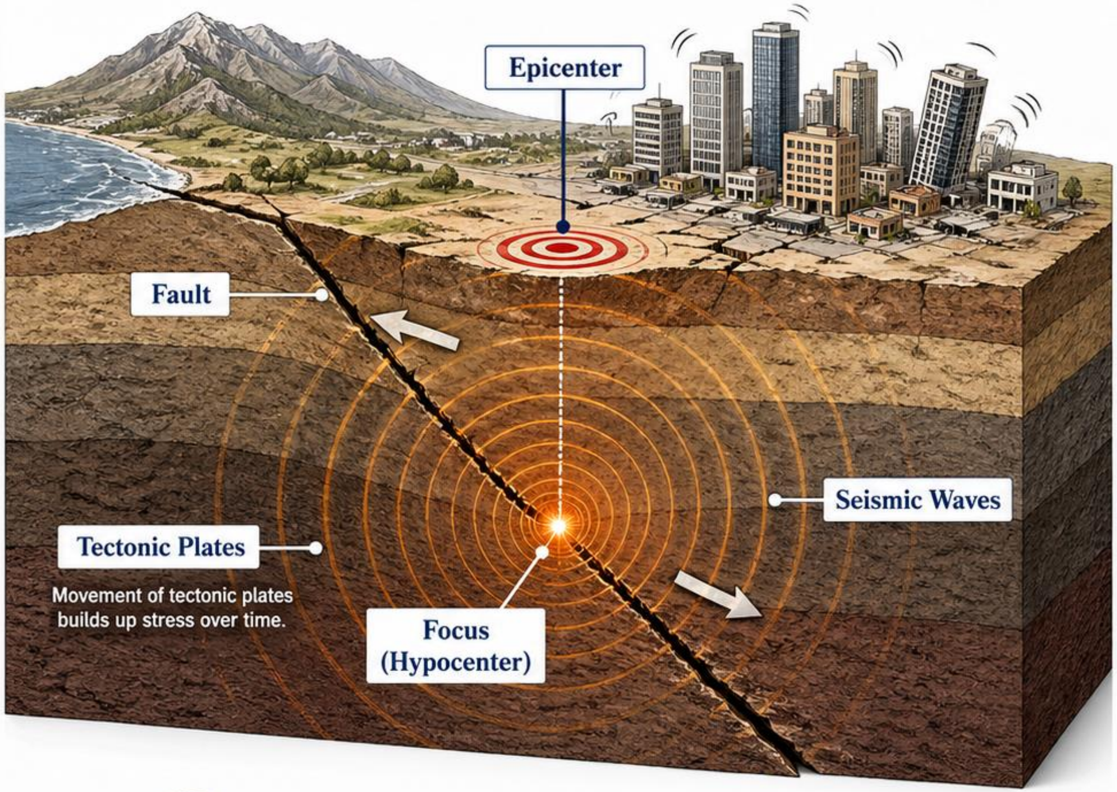
Examples: Earthquakes, wind speed, rainfall, ocean waves, traffic loads, structural vibrations.

Why it matters: Understanding random phenomena helps engineers estimate risk, predict possible responses, and design safer structures under uncertain loading.

Earthquakes are a clear example of a random phenomenon because their time, location, magnitude, duration, and frequency content cannot be known exactly in advance.

Key idea: Random phenomena are uncertain events, but they can be analyzed using probability and statistics.

What Is an Earthquake?



Definition

An earthquake is one of the most destructive and unpredictable natural phenomena. It occurs when energy is suddenly released within the Earth's crust, generating seismic waves that shake the ground.

How it affects us

- Ground vibration transmitted through soil layers to structures
- Secondary hazards such as tsunamis, fires, and landslides
- Can affect people and infrastructure almost anywhere on Earth

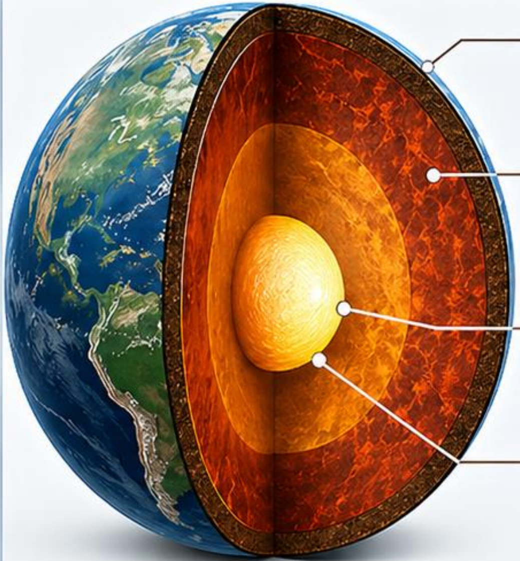
Why it is considered random

Earthquake excitation is non-deterministic: its occurrence time, intensity, duration, and frequency content cannot be predicted exactly. In engineering, it is therefore treated as a stochastic phenomenon and described using probabilistic methods rather than a purely deterministic model.

Key idea: Earthquake ground motion is a random vibration transmitted through the soil to buildings.

Earth Structure and Tectonic Plates

1. EARTH STRUCTURE



Crust
thin outer solid layer.

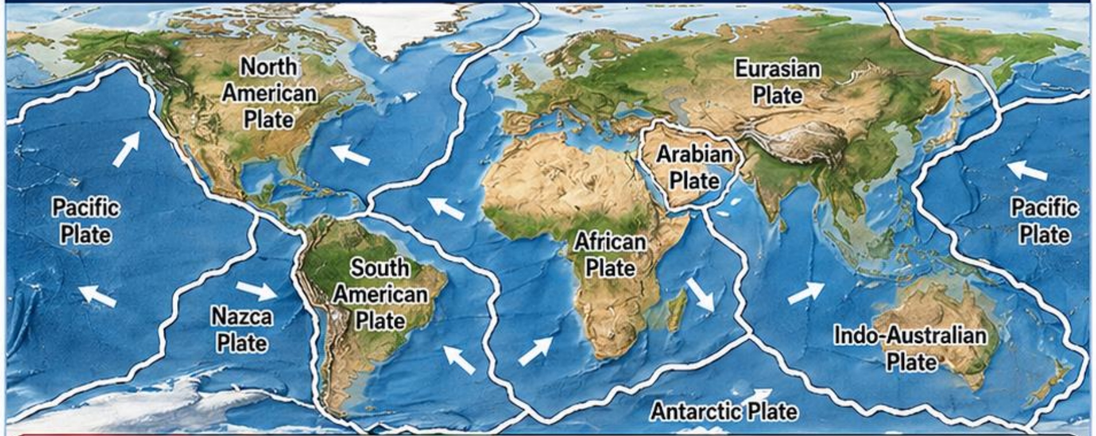
Mantle
thick hot semi-solid rock layer.

Outer Core
liquid iron-nickel layer.

Inner Core
solid iron-nickel center.

The Earth is composed of concentric layers with different physical and chemical properties.

2. TECTONIC PLATES



Convergent Boundary

Plates move toward each other. One may go beneath the other, causing volcanoes and earthquakes.

Divergent Boundary

Plates move away from each other. Magma rises, creating new crust and causing earthquakes.

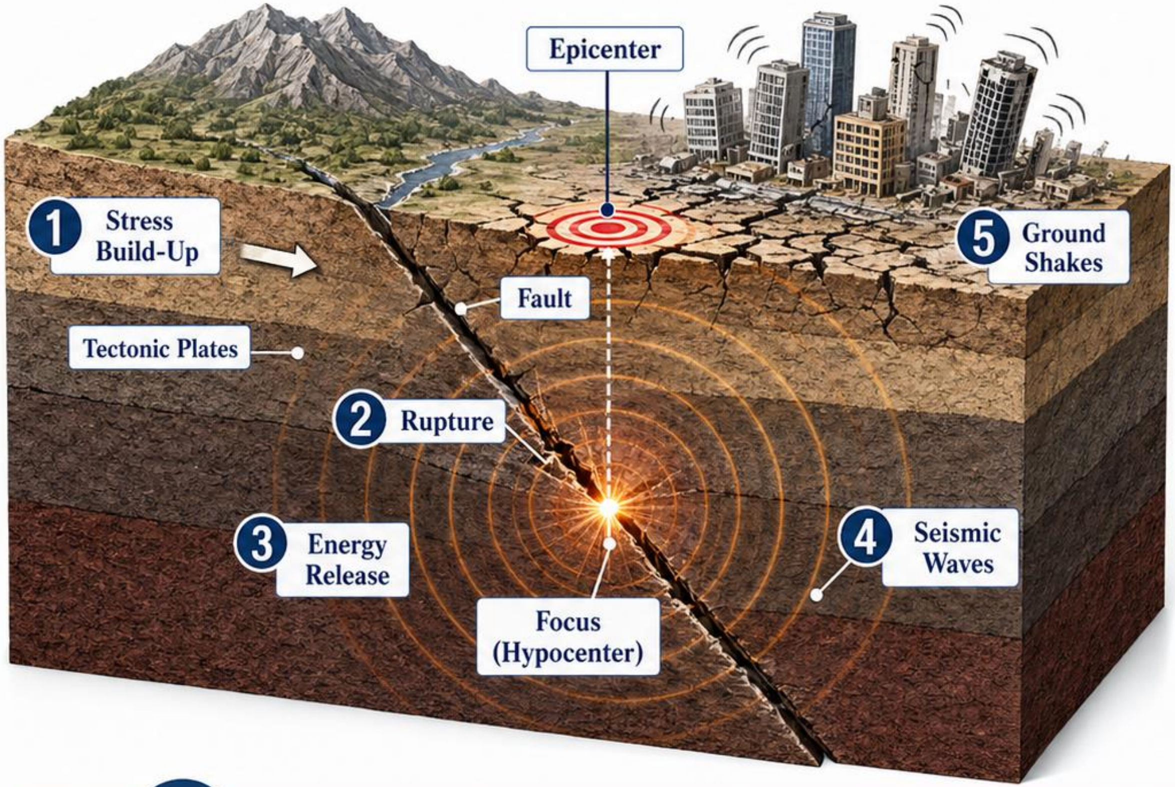
Transform Boundary

Plates slide past each other horizontally, causing earthquakes.

The lithosphere is divided into tectonic plates that move slowly over the asthenosphere. Their interaction at convergent, divergent, and transform boundaries causes earthquakes, volcanoes, and mountain building.

Why it matters: Most earthquakes occur along plate boundaries where stress builds up and is suddenly released.

How Earthquakes Occur



Step 1: Stress accumulation

Tectonic plates move slowly, but friction along faults prevents smooth motion. Stress gradually builds up in the rocks.

Step 2: Sudden rupture

When the accumulated stress exceeds the strength of the rocks, the fault ruptures and the blocks slip suddenly.

Step 3: Energy release

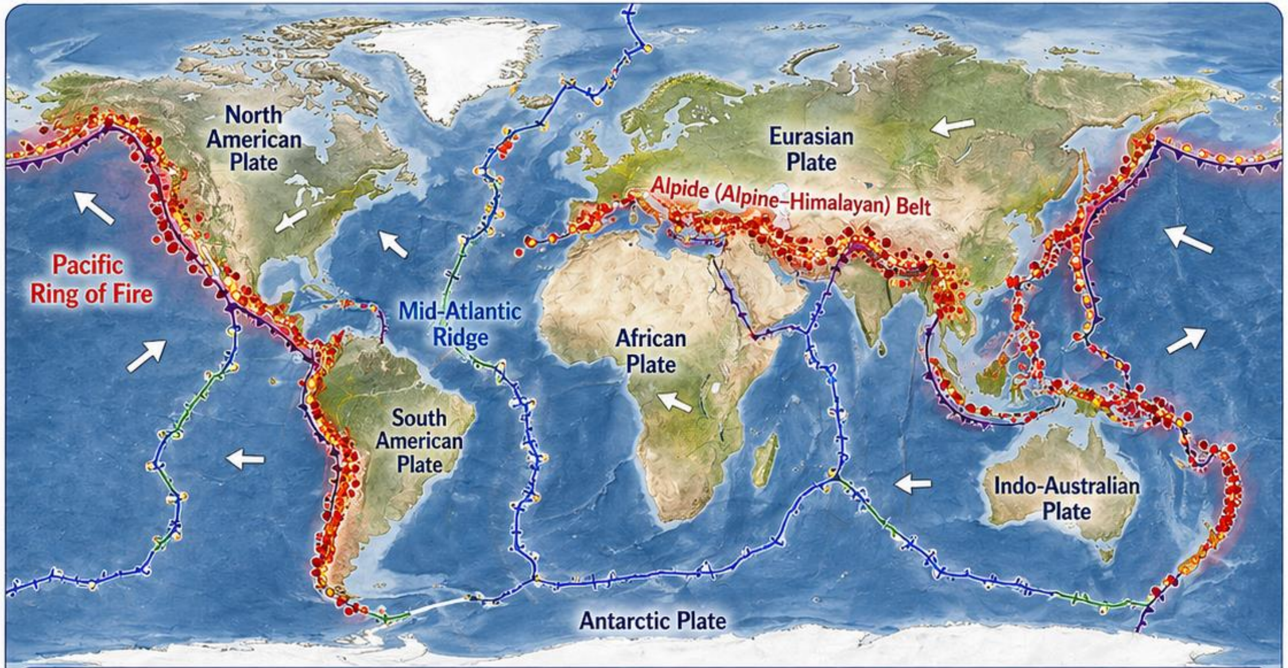
The sudden slip releases stored elastic energy as seismic waves, which travel through the Earth and shake the ground.

Elastic rebound concept

After rupture, the rocks rebound toward a less deformed state, releasing the energy that caused the earthquake.

Key idea: Earthquakes occur when stress built up by plate motion is suddenly released along a fault.

Where Earthquakes Happen



- Earthquake epicenters (shallow to deep)
- Convergent boundary (plates collide)
- Divergent boundary (plates move apart)
- Transform boundary (plates slide past)
- Direction of plate motion

Key idea: Earthquakes are concentrated mainly along plate boundaries, especially around the Pacific Ring of Fire and other active tectonic belts.

1 Main locations

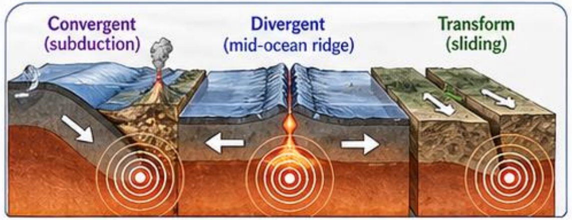
Most earthquakes occur along tectonic plate boundaries where plates converge, diverge, or slide past one another.

2 Key earthquake zones

- Pacific Ring of Fire
- Subduction zones
- Transform faults
- Mid-ocean ridges
- Collision belts such as the Himalayas and Mediterranean region

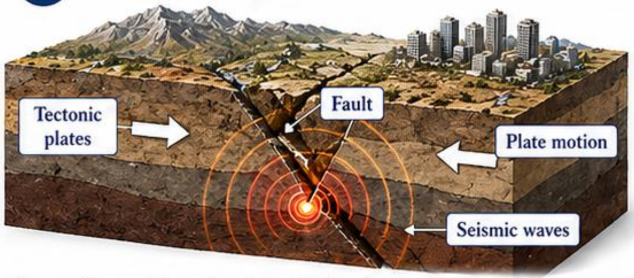
3 Intraplate earthquakes

Some earthquakes also occur inside plates, away from boundaries, but they are less common.



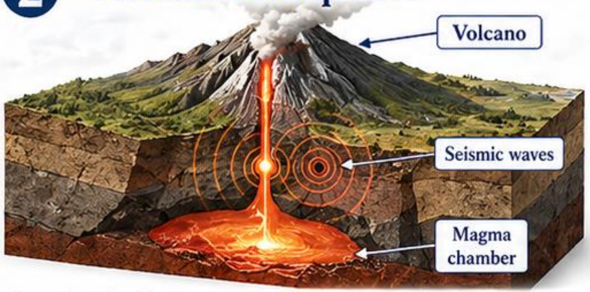
Types of Earthquakes

1 Tectonic earthquakes



Caused by sudden slip along faults due to plate motion and stress release. These are the most common type.

2 Volcanic earthquakes

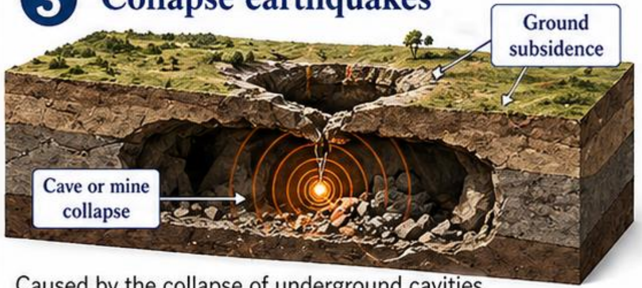


Associated with magma movement and volcanic activity, including eruptions and gas release.

Main classification

- **Tectonic:** produced by movement of the Earth's plates.
- **Volcanic:** related to magma movement and eruptions.
- **Collapse:** caused by failure of underground voids.
- **Induced:** triggered by human activities.

3 Collapse earthquakes



Caused by the collapse of underground cavities, such as caves, mines, or salt caverns.

4 Induced (human-caused) earthquakes

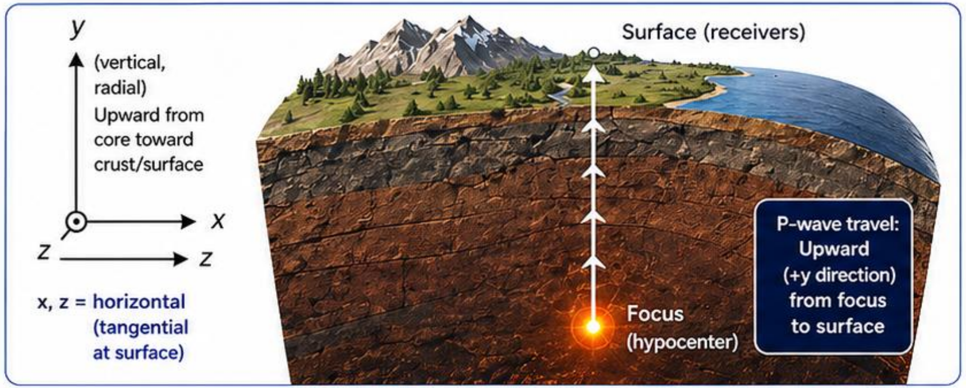
Linked to human activities such as mining, reservoir impoundment, oil and gas extraction, or fluid injection.

Additional ways to classify earthquakes

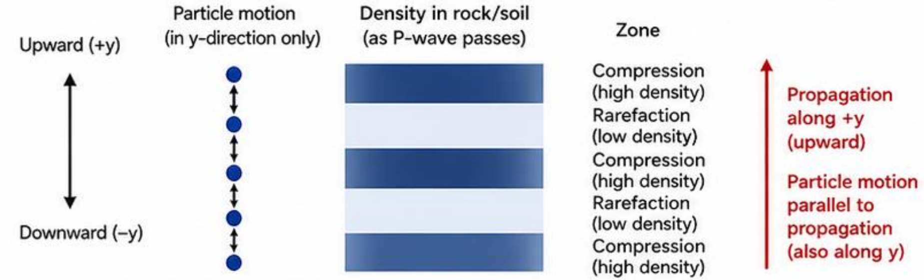
- **By depth:** shallow, intermediate, deep-focus.
- **By location:** interplate and intraplate.
- **By cause:** natural and induced.

Key idea: Earthquakes can be classified by their origin, and most damaging events are tectonic earthquakes associated with active faults and plate boundaries.

P-Waves (Primary Waves)



PARTICLE MOTION AND DENSITY CHANGES (LONGITUDINAL / COMPRESSIONAL)



P-waves travel upward (+y). Particles oscillate up and down in the y-direction only, causing alternating compressions (high density) and rarefactions (low density) vertically through the crust.

DEFINITION

For this slide's assumed axes:

P-waves (Primary waves) are **longitudinal (compressional) body waves** that are produced by an earthquake and travel through the Earth.

They propagate in the +y direction (upward, radial—from the focus toward the surface).

Particle motion is also in the y-direction and parallel to the direction of travel. This causes alternating increases and decreases in density (compressions and rarefactions) vertically through soil and rock layers.

HOW PARTICLES MOVE

- Particles vibrate in the y-direction only (up and down).
- Motion is parallel to the direction of wave travel (+y).
- This creates alternating **compressions** and **rarefactions**.
- The wave transmits **changes** in **pressure** through the medium.

DAMAGE LEVEL:
Usually lower than S-waves.

MAIN CHARACTERISTICS

- P-waves are the **fastest** seismic waves and **arrive first**.
- Body waves that travel through the interior of the Earth.
- **Longitudinal / compressional:** particle motion is parallel to propagation (+y).
- Produce alternating compressions (high density) and **rarefactions** (low density) vertically.
- They usually cause **less damage** than S-waves.
- Often felt as a sudden **push–pull** or "thud".

ENGINEERING SIGNIFICANCE

- Arrive **first** and provide the **earliest warning** in seismic monitoring and early warning systems.
- Help seismologists locate **earthquakes** and image the Earth's interior.
- Typically cause **less structural damage**, but can still be felt and startle occupants.

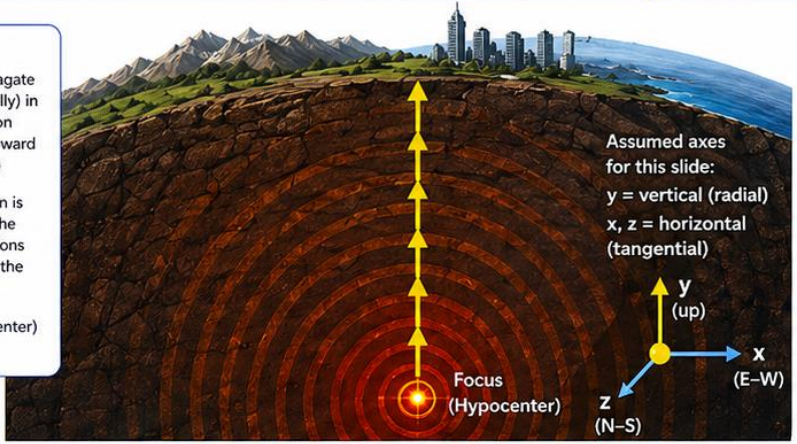
KEY IDEA:

In this example, P-waves travel **radially/vertically upward (+y)** from the focus to the surface. Particles shake in the **same y-direction** as the wave (parallel motion), producing **compressions and rarefactions** and **vertical changes in density** in soil and rock layers.

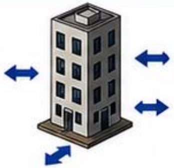
S-Waves (Secondary Waves)

LEGEND

- S-waves propagate upward (radially) in the +y direction (from focus toward crust/surface)
- Particle motion is horizontal in the x and z directions (tangential to the surface)
- Focus (hypocenter) at depth



EFFECTS ON STRUCTURES



S-waves produce strong side-to-side (E–W) and front-to-back (N–S) shear shaking. This causes large shear stresses and horizontal deformation in buildings.

DEFINITION

- S-waves (Secondary waves) are **transverse (shear) body waves.**
- They propagate **upward (radially)** from the focus through the Earth in the **+y (vertical) direction.**
- Particle motion is perpendicular to propagation and occurs only in the **horizontal x and z directions (tangential to the surface).**
- They shake the ground **side-to-side (E–W)** and **front-to-back (N–S).**
- They **do not** cause particle motion in the **vertical (y)** direction.

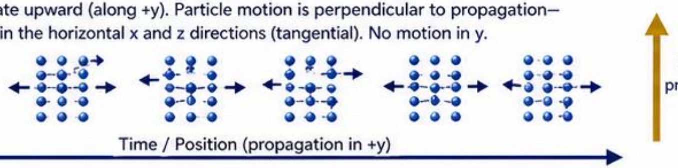
MAIN CHARACTERISTICS

- S-waves are **slower** than P-waves and arrive **second.**
- They are **body waves.**
- Particle motion is **transverse** (perpendicular to travel).
- They travel upward through solids; **not in liquids or gases.**
- Usually cause **stronger shaking and more damage** than P-waves.
- Often responsible for much of the **destructive ground motion.**

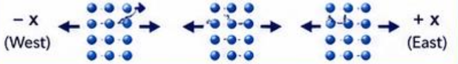
HOW PARTICLES MOVE (TRANSVERSE / SHEAR)

S-waves propagate upward (along +y). Particle motion is perpendicular to propagation—only in the horizontal x and z directions (tangential). No motion in y.

View in horizontal plane (at the surface)



Side-to-side shear (x-direction, E–W)



Front-back shear (z-direction, N–S)

Particles move horizontally in x or z, while the wave travels upward (+y).
There is **no** particle motion in the y (vertical) direction.

HOW PARTICLES MOVE

- Particles vibrate **horizontally** in the **x (E–W)** and **z (N–S)** directions.
- This motion is perpendicular to the upward (+y) direction of propagation.
- This is **shear (transverse)** motion.
- The wave transmits shear stress through the solid medium.

ENGINEERING SIGNIFICANCE

- S-waves usually cause **stronger shaking** and **greater damage** than P-waves.
- Often responsible for much of the **structural damage.**
- Particularly damaging to buildings and structures due to side-to-side (E–W) and **front-to-back (N–S) shear motion.**

COMPARISON NOTE (WARNING)

P-waves (compressional) mainly cause push-pull (dilation/compression) parallel to travel and usually produce less structural damage.

S-waves (shear) cause horizontal shear stresses, which are more damaging to buildings.

DAMAGE LEVEL:

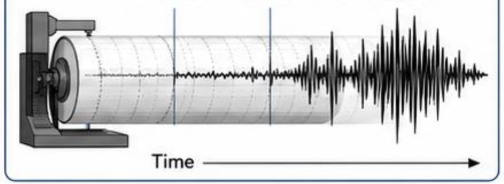
Usually higher than P-waves.

S-waves cause **greater damage** than P-waves because they create **stronger horizontal shear shaking** that structures are more vulnerable to.

KEY IDEA: In this example, S-waves are **transverse (shear) body waves** that travel **upward (radially)** in **+y** from the focus, but shake particles **tangentially** in the **horizontal x (E–W)** and **z (N–S)** directions. This horizontal shear motion produces strong side-to-side and front-to-back shaking, making S-waves generally **more destructive** for buildings.

Measuring Earthquakes

1 Magnitude



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

- **Richter Scale:** older local magnitude scale, useful historically.
- **Moment Magnitude Scale (Mw):** the modern standard, based on fault area, slip, and rock rigidity.

Micro	Minor	Light	Moderate	Strong	Major	Great
< 3	3–3.9	4–4.9	5–5.9	6–6.9	7–7.9	8+

Increasing magnitude and energy →

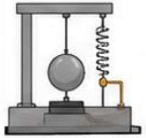
2 Intensity

Intensity describes the observed effects and damage at a specific location.

- **Modified Mercalli Intensity (MMI)** is the most widely used intensity scale.

MMI	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Descriptor	Not felt	Weak	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Very violent	Extreme	Extreme (near total)

4 How earthquakes are recorded



Seismic waves detected → Ground motion recorded → Data used to estimate magnitude and locate the event

Magnitude vs Intensity

Magnitude	Intensity
One value for the whole earthquake.	Varies from place to place.
Based on instrumental measurement.	Based on observed shaking and damage.
Represents the energy released at the source.	Depends on distance, geology, and local site conditions.

5 Key instruments and data

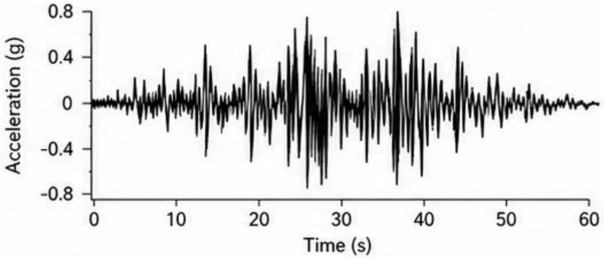
- **Seismometer** – detects ground motion.
- **Seismograph** – records the motion over time.
- **Seismogram** – the recorded waveform.
- **Epicenter location from station network** – computed using arrival times of seismic waves.

Key Idea

Magnitude measures the size and released energy of an earthquake, while intensity measures its effects on people, buildings, and the ground surface.

Random Nature of Earthquake Motion

1 Why earthquake motion is random

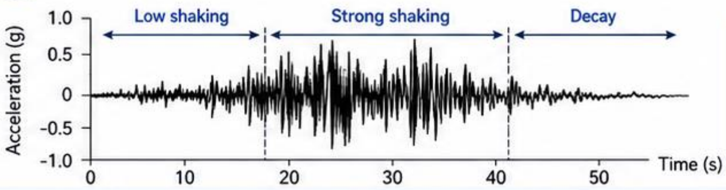


- Exact time of occurrence is uncertain.
- Amplitude changes irregularly with time.
- Frequency content varies during the event.
- Duration differs from one earthquake to another.
- Each ground-motion record is unique.

2 Main sources of uncertainty

- Uncertain magnitude
- Fault rupture process
- Uncertain epicenter / distance
- Wave propagation and reflections
- Local soil conditions
- Site amplification effects

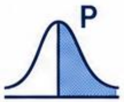
3 Time-domain behavior



Earthquake excitation is nonstationary and changes with time.

4 Statistical description

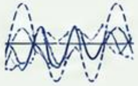
Because earthquake motion cannot be described exactly in deterministic terms, engineers use probabilistic / stochastic methods.



- Mean and variance
- RMS value
- Probability distribution
- Autocorrelation
- Power Spectral Density (PSD)

5 From deterministic to stochastic description

Deterministic		Stochastic
Known excitation Predictable at every instant Fixed time history	VS	Uncertain excitation Described statistically Many possible realizations



6 Engineering significance

- Real earthquake loads are uncertain.
- Structures must be designed for variability.
- Random vibration methods improve safety assessment.
- Probabilistic modeling gives more realistic predictions.

Key Idea

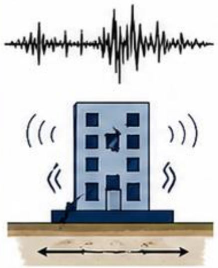
Earthquake ground motion is a random, non-deterministic excitation. Its exact behavior cannot be predicted in advance, so it is analyzed statistically using stochastic and random vibration concepts.

Effects of Earthquakes

Primary effects
Direct results of faulting and seismic wave action.

Secondary effects
Triggered by ground shaking or surface deformation.

1 Ground Shaking

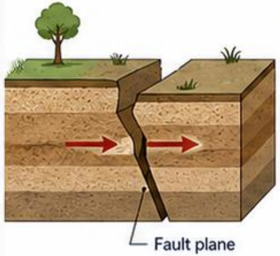


- Seismic waves cause sudden ground acceleration and displacement.
- Intensity depends on distance, magnitude, soil conditions, and structure response.

2 Structural Damage

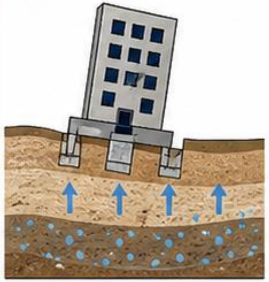
- Cracks, spalling, column failure, and collapse can occur.
- Affects buildings, bridges, roads, and critical lifeline systems.

3 Surface Rupture & Ground Failure



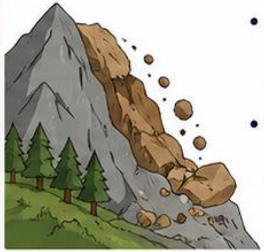
- Faulting can break the ground surface.
- Causes permanent offset, cracking, and damage to structures and infrastructure.

4 Soil Liquefaction & Settlement



- Loss of soil strength in saturated, loose sands during shaking.
- Leads to sinking, tilting, lateral spreading, and settlement.

5 Landslides & Rockfalls



- Strong shaking can trigger slope failures and rockfalls.
- Threatens communities, roads, railways, and dams.

6 Tsunamis

- Undersea earthquakes can displace large volumes of water.
- Generates long-period sea waves that can cause severe coastal inundation.

7 Fire, Utilities, and Infrastructure Disruption

Gas leaks and fires | Water main breaks | Road and rail damage | Power outages

- Damage to lifelines can trigger fires, leaks, outages, and service interruptions.
- Disrupts emergency response and recovery.

8 Human, Social, and Economic Effects

Casualties & Injuries | Displacement & Shelter Needs | Economic Losses & Downtime

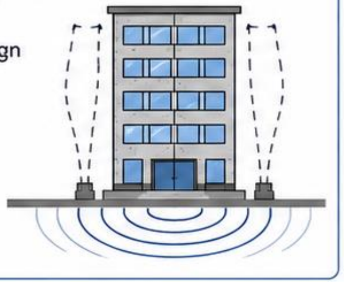
- Loss of life and long-term health impacts.
- Displacement, psychological stress, and major economic losses.

Key Idea | Earthquakes produce both primary and secondary effects, ranging from ground shaking and structural damage to liquefaction, landslides, tsunamis, and major social and economic losses.

Earthquake-Resistant Structures

1 Main Objective

Earthquake-resistant design aims to protect life, limit structural damage, and maintain functionality during and after earthquakes.

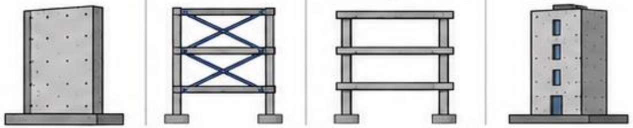


2 Key Design Principles

- **Strength:** resist seismic forces.
- **Stiffness:** control excessive drift.
- **Ductility:** deform without sudden failure.
- **Energy dissipation:** reduce vibration effects.
- **Regularity:** simple and symmetric layout performs better.

3 Structural Systems

Shear Walls | Braced Frames | Moment-Resisting Frames | Core Systems



Lateral load-resisting systems are essential for earthquake safety.

4 Important Earthquake-Resistant Features

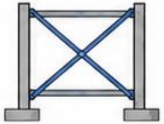
Base Isolation

Isolates the structure from ground motion.

Dampers / Energy Dissipation Devices

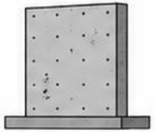
Absorb and dissipate seismic energy to reduce vibrations.

Cross Bracing



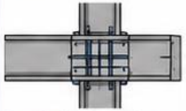
Increases lateral strength and stiffness.

Shear Walls



Resist lateral forces and reduce drift.

Flexible but Well-Detailed Joints



Provide ductility and ensure proper force transfer.

Strong Foundation and Good Soil Consideration

Ensure stability and reduce seismic amplification.

5 Good Seismic Design Practices

- Avoid soft story irregularities.
- Provide continuous load path.
- Ensure proper reinforcement detailing.
- Reduce heavy overhangs and torsional irregularity.
- Follow seismic building codes.

6 Retrofitting Existing Buildings

Before

After

- Jacketing of columns
- Adding shear walls or braces
- Base isolation upgrade
- FRP or steel strengthening
- Foundation improvement

7 Engineering Significance

- Reduces collapse risk.
- Protects occupants.
- Minimizes economic losses.
- Improves post-earthquake resilience.

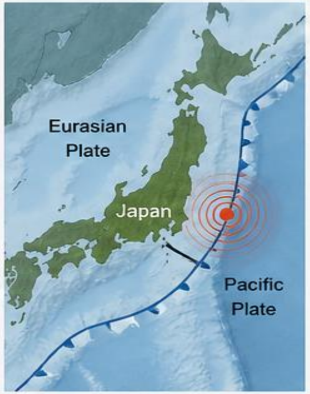
Key Idea | Earthquake-resistant structures are designed to safely resist ground shaking through strength, ductility, energy dissipation, and proper structural detailing.

CASE STUDY: 2011 TOHOKU EARTHQUAKE, JAPAN

One of the most powerful earthquakes recorded – a major event that reshaped earthquake science, engineering, and disaster preparedness.

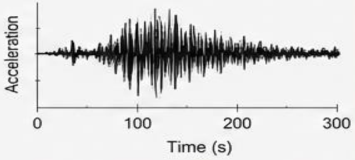
1. EVENT OVERVIEW

- **Date:** March 11, 2011
- **Magnitude:** Mw 9.0–9.1
- **Location:** Off the Pacific coast of Tohoku, Japan
- **Depth:** ~29 km
- **Type:** Megathrust (subduction zone)



2. GROUND MOTION

Strong and long-duration shaking recorded over a wide area.



Characteristics:

- Long duration (up to 6 minutes)
- Large amplitudes
- Significant energy in long periods

3. IMPACTS

- **Fatalities:** ~18,500+
- **Injured:** ~6,000
- **Buildings damaged/destroyed:** ~400,000+
- **Tsunami height:** Up to 40 m (extreme local run-up)
- **Nuclear accident:** Fukushima Daiichi
- **Economic loss:** ~US$ 235 billion

4. ENGINEERING & PERFORMANCE LESSONS

What Performed Well

- Modern high-rise buildings showed good performance
- Base isolation and damping systems effective
- Bridges with seismic design standards mostly remained operational
- Early warning system reduced some impacts

Base-isolated building in Sendai

What Did Not Perform Well

- Low-rise and non-ductile RC buildings suffered severe damage
- Liquefaction caused tilting and settlement
- Coastal structures overtopped by tsunami
- Older design codes underestimated seismic demand

Liquefaction-induced building tilt

5. KEY TAKEAWAYS

- Megathrust earthquakes can produce extreme shaking and tsunamis.
- Long-duration earthquakes are critical for the design of tall buildings.
- Land use planning and tsunami mitigation save lives.
- Continuous improvement of codes, monitoring, and preparedness is essential.

6. LASTING LEGACY

- Major updates to seismic design codes in Japan and worldwide
- Advances in tsunami warning systems
- Increased global awareness and research on megathrust earthquakes

“The 2011 Tohoku Earthquake reminds us that while we cannot prevent earthquakes, we can learn, adapt, and build a more resilient future.”

CONCLUSION

Building Knowledge, Resilience, and a Safer Future

Earthquakes are natural and unpredictable, but their impacts are not always inevitable. **Science, engineering, and preparedness empower us to reduce risk and save lives.**

1. UNDERSTAND THE PHENOMENON

Earthquakes result from the release of energy in the Earth's crust, producing complex ground motions with a random nature.

2. MEASURE AND ANALYZE

Through seismology and modern instruments, we can measure earthquakes, analyze their characteristics, and improve our understanding.

3. RECOGNIZE THE IMPACTS

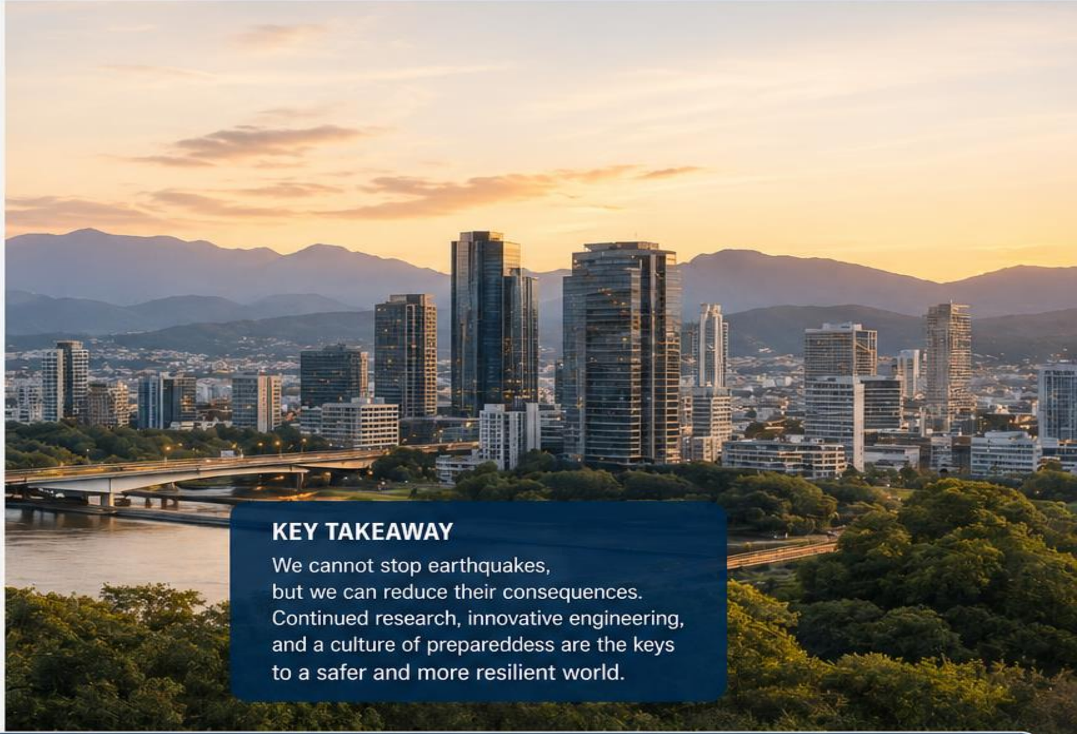
Earthquakes can cause loss of life, damage to infrastructure, and long-term social and economic disruptions.

4. BUILD RESILIENCE

Earthquake-resistant design, strict code enforcement, and retrofitting existing structures significantly reduce risks.

5. PREPARE AND ACT TOGETHER

Prepared communities, effective early warning systems, and public awareness are essential to minimize losses and ensure rapid recovery.



KEY TAKEAWAY

We cannot stop earthquakes, but we can reduce their consequences. Continued research, innovative engineering, and a culture of prepareddess are the keys to a safer and more resilient world.

A RESILIENT FUTURE IS BUILT TODAY

By combining knowledge, technology, and collaboration, we can protect communities and build a sustainable future in harmony with the forces of nature.

- Advance Research
- Strengthen Engineering
- Empower Communities
- Ensure Resilience

THANK YOU

FOR LISTENING

Your attention is appreciated