GY111 Physical Geology

Earthquakes and Seismic Waves
Earthquake Mechanisms

• Brittle Mechanical Model: “stick-slip”
• Focal point: 3D point inside the lithosphere where the seismic event occurs
• Epicenter: projection of focal point to the map surface
Seismic Energy Release

- Radiates from focal point.
- P-waves: compressional (fastest).
- S-waves: shear.
- Surface waves: move only on surface (slowest); cause damage to structures.
Seismic Wave Mechanics

- P-waves always travel faster than S-waves.
- Surface waves are slowest.
Seismic Wave Summary

• P(compressional)-waves: move fastest (7-10/sec), vibration direction parallel to wave path. Transmitted through all materials.

• S(shear)-waves: intermediate speed (4-6 km/sec), vibration direction perpendicular to wave path. Can only be transmitted through solid material.

• Surface waves: move along rock/air interface, created by energy transfer from P wave and S waves. These waves cause damage to man-made structures.
Seismic Wave Reflection

- P- and S-waves will reflect off of a surface that represents a density contrast. An example would be the crust/mantle boundary (2.8 vs. 3.1 g/cm³ respectively).
- When waves reflect they will do so at the same angle as their angle of incidence.

<table>
<thead>
<tr>
<th>Incidence angle</th>
<th>Reflection angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>D2 &gt; D1</td>
</tr>
<tr>
<td>D2</td>
<td></td>
</tr>
</tbody>
</table>
Seismic Wave Refraction

- Refraction: the angular “bend” of a wave that passes density boundary.
- Why is the path in the adjacent diagram curved?
- As density increases with depth so does transmission velocity.

**Diagram:**

- **Incidence angle**
- **Refraction angle**
- D1
- D2
- D2 > D1
Snell’s Law

• Snell’s Law: calculates the refracted angles of incidence across different velocity layers.

• Note that at some critical angle \(i\) that \(r = 90\) so all wave energy is reflected.

• Suppose \(v_1 = 5000\text{m/sec}\); \(v_2 = 10000\text{m/sec}\) and \(i = 30\) degrees therefore:
  
  – \( \sin r = \sin i \frac{v_2}{v_1} = 0.5(2.0) \)
  
  – \( r = \text{Arcsine}(1.0) = 90\) degrees
Example of Reflection vs. Refraction

- Note that both the reflected ray and refracted ray are shown.
- The refracted ray is more intense.
- The reflected angle = the incident angle (60).
- The refracted angle (35) is not equal to the incident angle (60).
Locating the Epicenter

- Requires readings from 3 seismic stations at 3 different geographic locations
Seismic Moment Magnitude

- Richter scale is similar
- Measured from deflection of pen on seismograph
Earthquakes & Plate Tectonics

- Distribution of epicenters outline plate boundaries
Focal Depth

- Deep focal point earthquakes occur only in subduction zones.
- Only shallow focal points are found along divergent ocean ridge systems.

**Mid-ocean ridge (divergence):**
- Normal faulting
- Transform fault (lateral shearing)
- Rift valley (divergence)

**Deep-ocean trench (convergence):**
- Lithosphere
- Asthenosphere

Shallow earthquakes coincide with normal faulting at divergent boundaries and with strike-slip faulting at transform boundaries.

Large shallow earthquakes occur mainly on thrust faults at the plate boundary.

Intermediate-focus earthquakes occur in the descending slab.

Deep-focus earthquakes also occur in the descending slab.
Focal Point Depth and Plate Tectonics

• Divergent Boundaries: only shallow depth seismic events (< 7km).
• Transform Boundaries: shallow to intermediate (1 – 35 km).
• Convergent Boundaries: shallow to deep focal points (1 – 700 km).
Deep Focal Point Seismicity

- The lithosphere is normally a maximum of 35 km depth so deep earthquakes should be impossible.
- The fact that 700 km deep seismicity occurs can only be explained by subduction moving brittle material rapidly into the mantle.
Subduction Zone Dip Angle

- The geographic distribution of focal point depths determines the dip angle of the subduction zone:
  - If shallow, intermediate, and deep focal point earthquakes occur in a narrow zone the dip of the subduction zone is steep.
  - If shallow, intermediate, and deep focal point earthquakes occur in a wide belt the dip on the subduction zone is shallow.
Subduction Zone Dip Examples

• Tonga Trench (A): shallow, int., and deep focal points occur in a narrow belt.

• Andean subduction zone (B): shallow, int. and deep focal points occur in a broad belt.
Tectonic Significance of Dip Variation on Subduction Zones

- Steep subduction zones occur when old (150 Ma) ocean lithosphere cools and become too dense to float on the asthenosphere.
- Shallow subduction occurs when young buoyant ocean lithosphere is forced to subduct under continental lithosphere. The ocean lithosphere “underplates” the continent causing unusually high mountains (Andes).
Earthquake Damage

- Direct destruction via surface waves.
- Landslides and ground failure.
- Tsunami.
- Fires.

![Diagram of Tsunami generation](image1)

*Computer simulation of tsunami radiation caused by a magnitude 7.7 earthquake in the Aleutian Islands.*

- 4 hr 42 min
- Hawaii
- North America

3 Main tsunami wave reaches Hawaiian Islands about 4.5 hours after the earthquake.
Tsunamis and Plate Tectonics

- Most tsunamis are generated at convergent plate boundaries.
- The subducted oceanic plate can have sudden vertical displacement of several tens of meters that moves the entire water column (3-10 km) vertically up or down.
- The generated tsunami radiates from the focal point at approximately 500 mph and may circle the globe several times before dissipating.
Tsunami Video

- Note that in the tsunami video there are not any giant breaking waves, rather tsunamis are more like a sudden rise in sea level everywhere along the shoreline.
- A major tsunami is preceded by a sudden drop in sea level exposing the sea floor.
- Just as destructive as the advance of sea water is the backwash movement as the tsunami recedes.
- Tsunamis may occur in several cycles – the first advance is not necessarily the most intense.

https://www.youtube.com/watch?v=wyOPau0gpFw
Tsunami Wave Physics

- Velocity = 800 kph (500 mph).
- Wavelength = 200 km in open ocean.
- Amplitude = 1-3 meters in open ocean.
- As the wave begins to “feel bottom” approaching the shoreline velocity drops to 80 kph (50 mph) but amplitude (wave height) grows to 30 m (100 feet) or more.
- Funnel shaped embayments may increase wave height even more.
Earthquake Damage Factors

- Bedrock composition or lack of bedrock
- Construction material and design.
- Proximity to focal point (focal depth).
- Earthquake magnitude.
- Structure periodicity.
Bedrock Composition

• Crystalline bedrock (metamorphic or igneous) is most resistant to earthquake damage.

• Soft-sediments or rocks with an inherent weakness (bedding, cleavage, joint fractures) are unstable during seismic wave vibration and may undergo liquefaction.

• Liquefaction: where a solid material transitions to liquid behavior because of some external factor (seismic waves).
Construction Material and Design

• Earthquake resistant structures contain an internal structural frame that can elastically bend to dissipate seismic wave energy (steel frame buildings).
• Brick and Cinder Block construction does not fare well under seismic surface waves.
• Wood frame buildings potentially are resistant if designed properly – but this is not generally the case.
• If seismic surface wavelength matches the periodicity of the structure it will not survive even low magnitude earthquakes.
Proximity to Focal Point

• Focal points range from surface level to >700 km.
• Deep earthquakes allow for energy to dissipate before reaching the surface.
• Rocks become stronger at greater depth therefore it takes massive stress levels to cause fault slip therefore most large magnitude earthquakes (>8.0) originate as deep focal points.
Earthquake Magnitude

- Magnitudes are measured by how violently a recording pen is deflected on a seismograph.
- Magnitude scales are exponential – each unit increase is 30 times the energy of lower magnitude.
- The point on the fault surface where the energy release begins is termed the focal point.
Structure Periodicity

• All structures have a vibration periodicity that is the time period of vibrations or rocking.

• If a seismic surface wave period matched the period of a building the building is doomed to fail.

• You can think of periodicity as the “period” of pendulum – the longer the pendulum arm the longer the period,

• For most seismic waves a 3-4 store building matches the periodicity of seismic surface waves.
Disaster Management Problems

- Transportation network destroyed.
- No emergency services.
- Power grid down.
- Many casualties.
- No communication.
- Food and water supplies limited.
- Sanitation difficult.
U.S. Seismic Risk

- Proximity to active fault zones.
- Nature of bedrock.
- Proximity of populations centers and infrastructure.
- Building codes.
Exam Summary

• Know differences between P-, S-, and surface waves.
• Be familiar with the stick-slip theory of earthquake propagation.
• Know how epicenters and focal points are located with seismic data.
• Be familiar with the association of earthquake types with various plate tectonic boundaries.
• Be familiar with the differences between wind-generated ocean waves and seismic sea waves (Tsunamis).
• Be familiar with reflection and refraction and Snell’s Law.