MODULE – 3

Wave Propagation
SOIL DYNAMICS

3D Case: Inclined Wave

Ray path, ray, and wavefront for (a) plane wave and (b) curved wavefront.

\[ \frac{\sin i}{v} = \text{constant} \]

Output of Reflected and Refracted waves from Incident wave (a) P-wave, (b) SV- wave, and (c) SH-wave.

Prof. Deepankar Choudhury, Department of Civil Engineering, IIT Bombay, Mumbai, India
Earthquake Waves

- The energy released during the earthquake travels as waves.

- Modern Seismograph can measure the intensity and duration of these waves in different directions.

- Seismogram is a visual record of arrival time and magnitude of shaking associated with seismic wave, generated by a seismograph.
Earthquake Waves

Earthquake Depth

Earthquakes usually occur at some depth below the ground surface. The depth can also be calculated from seismograph records.

Earthquake foci are described as:

- Shallow: less than 70 km depth
- Intermediate: 70 - 300 km depth
- Deep: 300 - 700 km depth

90% of earthquake foci are less than 100 km deep.

Large earthquakes are mostly at < 60 km depth.

No earthquakes occur deeper than 700 km.
Earthquake Waves

- Crust:
  - Continental crust (25-40 km*)
  - Oceanic crust (~6 km)
- Mantle
  - Upper mantle (650 km)
  - Lower mantle (2235 km)
- Core
  - Outer core: liquid (2270 km)
  - Inner core: solid (1216 km)

* Values represent the approximate thickness of each layer

**SOIL DYNAMICS**

Earthquake Waves

(Earthquake’s energy is transmitted through the earth as seismic waves)

- Two types of seismic waves
  - Body waves– transmit energy through earth’s interior
    - Primary (P) wave– rocks vibrate parallel to direction of wave
      - Compression and expansion (slinky example)
    - Secondary (S) wave– rocks move perpendicular to wave direction
      - Rock shearing (rope-like or ‘wave’ in a stadium)
  - Surface waves– transmit energy along earth’s surface
    - Rock moves from side to side like snake
    - Rolling pattern like ocean wave
Primary Wave

- P-waves, compressional or longitudinal.
- Typical crustal velocity: 6 km/s (~13,500 mph)
- Travel through solids, liquids, or gases
- Material movement is in the same direction as wave movement
- Behavior: Cause dilation and contraction (compression) of the earth material through which they pass.
- Arrival: They arrive first on a seismogram.

Even for P waves (which can travel all the way through) we see some changes in the path at certain points within Earth. This is due to the discontinuities present at different boundaries in earth structure.
Secondary Wave

- S waves (secondary)
- Typical crustal velocity: 3 km/s (~6,750 mph)
- Behavior: Cause shearing and stretching of the earth material through which they pass. Generally cause the most severe shaking; very damaging to structures.
- Travel through solids only
- shear waves - move material perpendicular to wave movement
- Arrival: Second on a seismogram.

S-wave velocity drops to zero at the core-mantle boundary or Gutenberg Discontinuity.
Earthquake Waves

M-Disc: The Mohorovicic discontinuity
G-disc: The Gutenberg discontinuity

Variations of P and S waves in earth
Earthquake Waves

**Surface Waves**

- Travel just below or along the ground’s surface
- Slower than body waves; rolling and side-to-side movement
- Especially damaging to buildings
Earthquake Waves

**Rayleigh Wave**
- Typical velocity: ~ 0.9 that of the S wave
- Behavior: Causes vertical together with back-and-forth horizontal motion. Motion is similar to that of being in a boat in the ocean when a swell moves past.
- Arrival: They usually arrive last on a seismogram.

**Love Wave**
- Typical velocity: Depends on earth structure, but less than velocity of S waves.
- Behavior: Causes shearing motion (horizontal) similar to S waves.
- Arrival: They usually arrive after the S wave and before the Rayleigh wave.
Earthquake Waves

Various earthquake waves

SOIL DYNAMICS

Earthquake Waves

Nature of P-wave

Push and pull

Extension Compression

Direction of energy transmitted

Nature of S-wave

Up and down

Side to side

Prof. Deepankar Choudhury, Department of Civil Engineering, IIT Bombay, Mumbai, India
Earthquake Waves

Nature of Love wave

Nature of Rayleigh wave

Locating Earthquake’s Epicenter

Seismic wave behavior

- **P** wave arrives first, then **S** wave, after that **L** and **R** waves
- After an earthquake, the difference in arrival times at a seismograph station can be used to calculate the distance from the seismograph to the epicenter (D).
SOIL DYNAMICS

If average speeds for all these waves are known, use S-P (S minus P) time formula to compute the distance (D) between a recording station and an event.

\[
\text{Time} = \frac{\text{Distance}}{\text{Velocity}}
\]

P wave has a velocity \( V_p \); S wave has a velocity \( V_s \).
\( V_s \) is less than \( V_p \).
Both originate at the same place—the hypocenter.
They travel the same distance
but the S wave takes more time than the P wave.

Time for the S wave to travel a distance D: \( T_s = \frac{D}{V_s} \).
Time for the P wave to travel a distance D: \( T_p = \frac{D}{V_p} \).

The time difference
\[
(T_s - T_p) = \frac{D}{V_s} - \frac{D}{V_p} = D \left( \frac{1}{V_s} - \frac{1}{V_p} \right) = D \left( \frac{V_p - V_s}{V_p V_s} \right)
\]

Now solve for the Distance D:
\[
D = \frac{V_p V_s}{V_p - V_s} (T_s - T_p)
\]

Earthquake Waves

3-circle method:

1) Read S-P time from 3 seismograms.
2) Compute distance for each event/recording station pair \( (D_1, D_2, D_3) \) using S-P time formula.
3) Draw each circle of radius \( D_i \) on map.
4) Overlapping point is the event location.

Assumption: Source is relatively shallow; epicenter is relatively close to hypocenter.
Earthquake Waves

1. Measure time between P and S wave on seismogram
2. Use travel-time graph to get distance to epicenter

Seismic Travel-time Curve:
If the speeds of the seismic waves are not known, use Travel-Time curve for that region to get the distance

END of
MODULE – 3
Wave Propagation