Chapter 26: Shear and Rayleigh Waves

Introduction

In Earthquake Engineering, understanding the different types of seismic waves is critical for assessing ground motion, structural response, and foundation design. Among these waves, **Shear Waves (S-waves)** and **Rayleigh Waves** play a dominant role in the propagation of energy through the Earth during seismic events. These waves exhibit unique propagation characteristics and interact differently with geological formations and structural systems.

This chapter delves into the physics, mathematical descriptions, propagation behavior, and engineering implications of Shear and Rayleigh waves. These insights are crucial for designing earthquake-resistant structures and interpreting seismic data for hazard assessment.

26.1 Seismic Wave Classification Recap

Before exploring S-waves and Rayleigh waves specifically, it is helpful to understand the broader classification of seismic waves:

- **Body Waves**: Travel through the interior of the Earth.
  - **P-waves (Primary or Compressional Waves)**
  - **S-waves (Secondary or Shear Waves)**
- **Surface Waves**: Travel along the Earth's surface.
  - **Rayleigh Waves**
  - **Love Waves**

This chapter focuses exclusively on **S-waves** and **Rayleigh Waves**, highlighting their characteristics, generation, and influence on structures.

26.2 Shear Waves (S-Waves)

26.2.1 Nature and Motion

- Shear waves are **transverse body waves** that cause particle motion **perpendicular to the direction of wave propagation**.
- Unlike P-waves, which compress and expand the material, S-waves **shear the ground sideways or up-and-down**.
- They do **not propagate through fluids**, making them absent in the Earth's outer core.

26.2.2 Mathematical Description

- Governed by the **wave equation for shear waves**:

$$\nabla^2 \mathbf{u} = \frac{1}{v_s^2} \frac{\partial^2 \mathbf{u}}{\partial t^2}$$

- where: $\mathbf{u}$ = displacement vector, v_s = shear wave velocity, t = time.
- Shear wave velocity is expressed as:

$$v_s = \sqrt{\frac{G}{\rho}}$$

- where: G = shear modulus of the medium, ρ = density of the medium.

26.2.3 Velocity and Attenuation

- **Velocity**: Slower than P-waves, but faster than surface waves.
- **Attenuation**: Higher than P-waves due to their transverse nature and energy dissipation in heterogeneous media.

26.2.4 Engineering Significance

- S-waves are **highly destructive** due to their high amplitude and ground shaking capability.
- Contribute significantly to **lateral forces** on structures.
- Understanding S-wave behavior is essential for:
  - Site-specific seismic hazard analysis,
  - Dynamic soil-structure interaction models,
  - Ground motion prediction equations (GMPEs).

26.3 Rayleigh Waves

26.3.1 Nature and Motion

- Rayleigh waves are **surface seismic waves** that travel along the Earth's surface in a **retrograde elliptical motion**.
- They combine longitudinal and vertical ground motion, similar to ocean waves.
- Particle motion: Ground particles move in **elliptical paths**, opposite to the direction of wave travel.

26.3.2 Mathematical Model

- Derived using **elastic half-space theory**, first developed by **Lord Rayleigh** in 1885.
- Displacement potential function approach is used to obtain the **Rayleigh wave solution**:

$$u(x, z, t) = Ae^{-\alpha z} \cos(kx - \omega t) + Be^{-\beta z} \sin(kx - \omega t)$$

- **Rayleigh wave velocity** (v_R) is slightly less than v_s, typically:

$$v_R \approx 0.9 \cdot v_s$$

- depending on Poisson's ratio of the medium.

26.3.3 Energy Distribution and Dispersion

- Rayleigh waves carry significant **seismic energy**, especially near the surface.
- **Dispersion** occurs in layered media – wave velocity varies with frequency and depth.
- Low-frequency Rayleigh waves penetrate deeper and affect taller structures.

26.3.4 Effects on Structures

- Induce both **vertical and horizontal shaking**, resulting in:
  - Differential settlement,
  - Resonance in flexible or tall buildings,
  - Ground amplification near soft soil layers.
- **Urban damage during earthquakes** is often linked to Rayleigh wave action.

26.4 Comparison between Shear and Rayleigh Waves

Feature	Shear Waves (S-Waves)	Rayleigh Waves
Type	Body wave	Surface wave
Particle Motion	Transverse (perpendicular to propagation)	Retrograde elliptical (vertical + longitudinal)
Speed	Moderate (slower than P-waves)	Slower than S-waves
Penetration	Through solid interior	Along the surface (few km depth)

Feature	Shear Waves (S-Waves)	Rayleigh Waves
Impact on Structures	High horizontal shear forces	Vertical and horizontal displacement
Damaging Potential	High	Very high near surface, especially in soft soils
Propagation Medium	Solids only	Solids (near-surface)

26.5 Applications in Earthquake Engineering

- **Site Response Analysis**: S-waves and Rayleigh waves are essential inputs for evaluating soil amplification and local site effects.
- **Seismic Hazard Mapping**: Understanding the propagation of these waves helps model ground motion for different regions.
- **Seismograph Interpretation**: Time delay between P, S, and Rayleigh arrivals is used to locate epicenters and estimate magnitudes.
- **Soil-Structure Interaction (SSI)**: Accurate modeling of these waves improves prediction of foundation behavior during seismic loading.
- **Seismic Design Codes**: Wave characteristics are reflected in building codes via spectral acceleration curves and design response spectra.

26.6 Laboratory and Field Measurement Techniques

26.6.1 S-Wave Measurement

- **Down-hole and Cross-hole Tests**: Determine S-wave velocity profile with depth.
- **Seismic Refraction**: Identifies velocity contrasts in subsurface layers.

26.6.2 Rayleigh Wave Testing

- **MASW (Multichannel Analysis of Surface Waves)**:
  - Uses surface array sensors to capture Rayleigh wave propagation.
  - Provides shear wave velocity profiles and stratification data.
- **Spectral Analysis of Surface Waves (SASW)**:
  - Frequency-domain approach for determining stiffness profiles.

26.7 Wave Amplification and Structural Resonance

- Soft soils significantly amplify **S and Rayleigh wave amplitudes**, increasing seismic hazard.

- Structures with natural frequencies matching Rayleigh wave frequencies experience **resonance**, leading to amplified vibrations.
- **Base isolation systems** are designed to reduce the transfer of Rayleigh-induced motion.

26.8 Numerical Modeling and Simulation

- Finite Element (FE) and Finite Difference Methods (FDM) are used to simulate wave propagation in heterogeneous media.
- Numerical tools model:
  - **Wave propagation paths**
  - **Interaction with geological layers**
  - **Time-history of ground shaking**

26.9 Case Studies of S and Rayleigh Wave Impacts

- **Mexico City Earthquake (1985)**:
  - Extensive damage due to Rayleigh wave amplification in lakebed sediments.
- **Kobe Earthquake (1995)**:
  - Notable S-wave generated structural collapses due to strong lateral motion.
- **Bhuj Earthquake (2001)**:
  - Amplification of both S and Rayleigh waves in sediment-filled basins.

26.10 Influence of Soil Type on Wave Propagation

Soil characteristics have a profound effect on the behavior of both S-waves and Rayleigh waves.

26.10.1 Soft vs. Hard Soils

- **Soft soils** tend to **amplify** both S and Rayleigh waves due to:
  - Low shear modulus,
  - High damping ratio,
  - Nonlinear stress-strain behavior.

- **Hard rock** or stiff soils transmit seismic waves more rapidly but with lesser amplification.

26.10.2 Layered Soil Profiles

- When a soft layer is sandwiched between stiff layers (or vice versa), **wave trapping** and **resonant amplification** may occur.
- **Rayleigh waves** are especially sensitive to near-surface layers and may show significant **dispersion** in such profiles.

26.10.3 Liquefaction and Wave Behavior

- During strong shaking, **saturated loose sands** may undergo **liquefaction**, drastically altering how shear and Rayleigh waves propagate.
- Energy dissipation mechanisms shift, potentially increasing horizontal displacements and settlement.

26.11 Effects of Local Geology and Topography

Seismic waves interact strongly with surface features and underground geological variations.

26.11.1 Basin and Valley Effects

- Rayleigh waves often get **trapped** in sedimentary basins, leading to:
  - Prolonged shaking duration,
  - Multiple reflections,
  - Higher amplitude waves.

26.11.2 Topographic Amplification

- Hilltops, ridges, and cliffs can **amplify** Rayleigh wave motion due to wave diffraction and focusing effects.
- Such amplification is not usually considered in basic design but must be accounted for in critical infrastructure.

26.11.3 Fault Zone Trapping

- In the vicinity of active faults, S and Rayleigh waves can be **channeled** along the fault zone, creating **directivity effects**.
- This results in highly localized damage patterns aligned with fault rupture.

26.12 Instrumentation for Monitoring S and Rayleigh Waves

26.12.1 Strong Motion Seismometers

- Installed in dense arrays to record **horizontal and vertical acceleration** data.
- Capable of distinguishing between P, S, and surface waves.

26.12.2 Surface Wave Arrays

- Arrays of geophones or accelerometers placed across a site to **capture surface wave velocity profiles**.
- Used for **site classification** and **microzonation** studies.

26.12.3 Interferometry and Ground-Based Radar

- Modern tools like **InSAR (Interferometric Synthetic Aperture Radar)** can detect surface displacements due to Rayleigh wave passage.
- Useful for post-earthquake ground deformation mapping.

26.13 Seismic Design Considerations Based on Wave Behavior

26.13.1 Response Spectra Development

- **Design response spectra** incorporate ground motion expected from S and Rayleigh waves.
- Spectral shapes vary for:
  - Rock vs soil sites,
  - Short vs tall structures,
  - Distance from fault rupture.

26.13.2 Building Configuration

- Shear waves cause **lateral loads**; structures must have:
  - Adequate **bracing**,
  - Proper **lateral load paths**,
  - Avoidance of **soft-storey designs**.
- Rayleigh wave effects on foundations include:
  - **Base tilting**,
  - **Differential settlements**,
  - Importance of **soil-structure interaction (SSI)** modeling.

26.13.3 Damping and Isolation Systems

- **Base isolators** and **dampers** are tuned to reduce the impact of low-frequency Rayleigh waves.
- High-rise buildings may use **tuned mass dampers (TMDs)** to minimize sway from S-wave induced motion.

26.14 Analytical Tools and Simulation Software

- Various tools and software packages are available for modeling wave propagation:

Software	Application	Features
SHAKE2000	Site response analysis	1D wave propagation (linear & equivalent-linear)
DEEPSOIL	Site-specific response	Can handle nonlinear soil behavior
FLAC	Wave propagation in soil and rock	Finite difference method
OpenSees	Advanced dynamic analysis	Customizable modules for S and surface wave simulation
SeismoSignal	Strong motion data analysis	Extracts parameters from real seismic events

These tools allow engineers to simulate the effects of seismic waves under a variety of scenarios and soil-structure systems.

26.15 Future Research and Trends

26.15.1 Real-Time Ground Motion Prediction

- Real-time modeling of **Rayleigh wavefront propagation** for earthquake early warning systems (EEWS).
- Use of **AI and machine learning** for wave pattern recognition.

26.15.2 Advanced Geophysical Imaging

- High-resolution subsurface imaging to capture **wave velocity anomalies**.
- Use of **ambient vibration testing** and **passive seismic arrays** to estimate Rayleigh wave dispersion.

26.15.3 Resilient Design Strategies

- Development of **wave-resistant foundation systems**.
- Integration of **smart materials and sensors** to detect and respond to S and Rayleigh wave effects dynamically.