Chapter 23: Elastic Rebound

Introduction

The phenomenon of elastic rebound is a foundational concept in the study of earthquakes and tectonic plate motion. It explains how energy is stored and suddenly released in the Earth's crust, resulting in seismic events. First proposed by geologist Harry Fielding Reid following the 1906 San Francisco earthquake, the theory describes how deformed rock masses in the Earth's crust behave elastically until their strength is exceeded, at which point the built-up strain is released through faulting.

This chapter delves deep into the mechanics of elastic rebound, its relationship with tectonic plate movement, and its significance in seismic hazard assessment and earthquake prediction models.

23.1 Tectonic Forces and Crustal Deformation

The Earth's lithosphere is divided into several tectonic plates that float over the semi-fluid asthenosphere. These plates constantly interact at their boundaries—converging, diverging, or sliding past each other—causing stress accumulation within the crust.

23.1.1 Types of Tectonic Plate Boundaries

- **Convergent Boundaries:** Plates move towards each other causing compression.
- **Divergent Boundaries:** Plates move apart, leading to tension.
- **Transform Boundaries:** Plates slide past each other, inducing shear stress.

23.1.2 Stress Accumulation

At these plate boundaries, friction prevents continuous movement. As a result, strain energy builds up over time in the rock masses. The rock deforms, storing elastic energy, until the stress exceeds the rock's yield strength.

23.2 The Elastic Rebound Theory

23.2.1 Historical Background

- Harry Reid developed the elastic rebound theory after observing land displacement from the 1906 San Francisco earthquake.

- Reid noted that land on either side of the San Andreas Fault moved in opposite directions before the quake and then suddenly snapped back during the quake.

23.2.2 Theory Explained

- When tectonic stress is applied to rock masses, they initially deform elastically.
- Over time, if the stress exceeds the material's elastic limit, rupture occurs at a fault.
- The rocks on either side of the fault rebound to a less deformed state, releasing the stored energy as seismic waves.

23.2.3 Key Features

- **Elastic strain accumulation**: Rocks behave like stretched rubber bands.
- **Sudden rupture and release**: Fault slips occur when accumulated stress surpasses frictional resistance.
- **Energy release**: The elastic energy is converted into seismic energy (P-waves, S-waves, and surface waves).

23.3 Mechanics of Elastic Rebound

23.3.1 Stress and Strain Curve

The relationship between stress and strain in rocks follows an initially linear (elastic) path:

- **Elastic region**: Stress and strain are proportional.
- **Yield point**: Beyond this, plastic deformation begins.
- **Fracture point**: Rupture occurs, marking fault slip initiation.

23.3.2 Fault Displacement

- Displacement is greatest at the fault and decreases with distance.
- The amount of fault slip correlates with the amount of elastic strain previously accumulated.

23.3.3 Elastic Energy Storage

- Elastic potential energy per unit volume = $\frac{1}{2}\sigma\epsilon$ where σ = stress and ϵ = strain.
- Energy builds up over years or centuries and is released in seconds during an earthquake.

23.4 Earthquake Cycle and Elastic Rebound

Elastic rebound is not a one-time event but part of a **cyclical process** known as the **earthquake cycle**.

23.4.1 Phases of the Earthquake Cycle

1. **Interseismic Phase**: Stress accumulates due to tectonic motion.
2. **Coseismic Phase**: Rapid fault slip and energy release during the quake.
3. **Postseismic Phase**: Stress redistribution and minor afterslips.
4. **Reaccumulation**: Process restarts as stress builds again.

23.4.2 Implications of the Earthquake Cycle

- Predictability: Allows for probabilistic forecasting of future earthquakes.
- Monitoring: GPS and strain gauges detect crustal deformation over time.

23.5 Evidence Supporting Elastic Rebound Theory

23.5.1 Geodetic Measurements

- GPS and InSAR (Interferometric Synthetic Aperture Radar) measure crustal deformation with high precision.
- Show clear patterns of land motion consistent with elastic strain accumulation and release.

23.5.2 Paleoseismology

- Studies of ancient fault scarps and trenching reveal evidence of repeated faulting events consistent with elastic rebound.

23.5.3 Laboratory Experiments

- Rock deformation under controlled stress demonstrates elastic behavior and sudden rupture similar to natural faulting.

23.6 Limitations and Extensions of the Theory

23.6.1 Limitations

- Not all earthquakes follow the ideal elastic rebound model.
- Some faults exhibit **aseismic creep** where stress is released gradually.
- In regions of complex geology, strain may be distributed over multiple faults.

23.6.2 Extensions

- **Rate-and-state friction models** add time-dependent behavior to elastic rebound theory.
- **Viscoelastic models** incorporate the ductile flow of deeper crustal materials.

23.7 Applications in Earthquake Engineering

23.7.1 Seismic Hazard Assessment

- Understanding where and how strain accumulates helps identify zones of high earthquake potential.

23.7.2 Building Codes

- Structures in zones of high strain accumulation are designed to withstand sudden energy release.

23.7.3 Early Warning Systems

- Continuous strain monitoring near active faults can serve as an early warning mechanism, though exact prediction remains elusive.

23.8 Real-World Case Studies

23.8.1 1906 San Francisco Earthquake

- Fault movement of ~6 meters observed.
- Elastic rebound explains sudden rupture and ground displacement.

23.8.2 1995 Kobe Earthquake (Japan)

- Preceded by decades of crustal deformation.
- Post-earthquake surveys showed significant rebound.

23.8.3 Himalayan Earthquakes

- Elastic rebound is a key process in thrust faults along the India-Eurasia collision zone.

23.9 Mathematical Modeling of Elastic Rebound

Elastic rebound can be quantitatively modeled using:

- **Dislocation theory**
- **Elastic half-space models**
- **Okada equations** for calculating surface deformation due to fault slip.

Example: The displacement $u(x)$ due to a fault slip D at depth h in an elastic half-space can be modeled as:

$$u(x) = \frac{D}{\pi} \cdot \frac{h}{x^2 + h^2}$$

Where:

- $u(x)$: Surface displacement at a horizontal distance x from the fault
- D: Slip on the fault
- h: Depth of fault

23.10 Monitoring and Prediction Techniques

23.10.1 Crustal Strain Monitoring

- GPS networks
- Tiltmeters
- Strainmeters

23.10.2 Seismic Networks

- Record foreshocks and microseismicity indicating strain accumulation.

23.10.3 Machine Learning Models

- Used to detect complex strain release patterns from large datasets.

23.11 Role of Elastic Rebound in Fault Mechanics

Elastic rebound plays a critical role in how faults behave under long-term tectonic stress.

23.11.1 Stick-Slip Behavior

- Describes the cyclical sticking and slipping behavior of fault surfaces.
- **Stick phase**: Accumulation of elastic strain.
- **Slip phase**: Sudden release of energy in the form of an earthquake.

23.11.2 Influence of Friction and Fault Properties

- Fault roughness, rock type, and pore pressure all influence the threshold at which rebound occurs.
- High-friction faults store more energy, resulting in more powerful earthquakes upon rupture.

23.11.3 Locked vs Creeping Faults

- **Locked Faults**: Fully restrained, ideal conditions for elastic rebound and large earthquakes.
- **Creeping Faults**: Exhibit continuous slip, releasing stress without significant quakes.

23.12 Elastic Rebound and Tsunamigenic Earthquakes

Tsunamis are often generated by megathrust earthquakes involving large vertical displacement on the seafloor.

23.12.1 Subduction Zone Mechanics

- Elastic rebound explains how stress builds up as one tectonic plate is forced under another.
- When the interface ruptures, the overriding plate rebounds upward, displacing large volumes of water.

23.12.2 Real-World Examples

- **2004 Indian Ocean Earthquake (Mw 9.1–9.3)**: Caused by a massive elastic rebound along the Sunda Trench.
- **2011 Tōhoku Earthquake (Mw 9.0)**: Sudden vertical uplift of the seafloor triggered a devastating tsunami.

23.13 Numerical Simulations of Elastic Rebound

With advancements in computational geomechanics, the elastic rebound process can now be simulated in detail.

23.13.1 Finite Element and Finite Difference Methods

- Used to model stress accumulation and rupture propagation on faults.
- Allow for variable material properties, non-linear behavior, and complex fault geometries.

23.13.2 Inverse Modeling

- Reconstructs past fault slip and deformation patterns from geodetic and seismic data.
- Helps validate the applicability of the elastic rebound model in specific tectonic settings.

23.14 Elastic Rebound in Reservoir-Induced and Induced Seismicity

23.14.1 Reservoir-Induced Seismicity

- Loading from reservoirs (e.g., dams) can cause stress perturbations leading to fault rupture.
- Elastic rebound principles apply when subsurface stress crosses critical thresholds.

23.14.2 Induced Seismicity from Human Activities

- Activities like deep fluid injection, mining, and hydraulic fracturing can alter stress fields.
- Elastic rebound may occur as the crust adjusts to these artificial loads.

23.15 Future Directions in Elastic Rebound Research

23.15.1 Integration with AI and Machine Learning

- AI models are increasingly used to predict strain accumulation and possible fault failure.
- Real-time monitoring data feed these models for dynamic hazard assessments.

23.15.2 Multidisciplinary Research

- Geologists, geophysicists, civil engineers, and data scientists are working together to refine our understanding of fault mechanics.
- Coupling of **seismic**, **geodetic**, and **hydrological data** is providing more holistic models.

23.15.3 Earthquake Forecasting Challenges

- Despite understanding elastic rebound, **precise prediction** of time, location, and magnitude remains elusive.
- Focus has shifted toward **risk mitigation** and **early warning**, rather than deterministic predictions.