Chapter 21: Geological Faults

Introduction

Geological faults are fractures or zones of fractures between two blocks of rock, along which movement has occurred. These structures are of paramount importance in earthquake engineering, as the majority of earthquakes originate due to sudden energy release along faults. Understanding the nature, classification, formation, and behavior of faults provides a scientific basis for assessing seismic hazards and designing earthquake-resistant infrastructure. Civil engineers must incorporate geological fault data during site selection, foundation design, and urban planning, especially in tectonically active regions.

21.1 Definition and Characteristics of Faults

A **fault** is defined as a fracture or discontinuity in the Earth's crust along which appreciable displacement has taken place due to tectonic forces. The block of rock on each side of the fault is displaced relative to the other.

Key characteristics include:

- **Displacement**: Movement along the fault plane.
- **Fault Plane**: The surface along which the movement has occurred.
- **Fault Scarp**: A cliff or step created by faulting.
- **Hanging Wall and Footwall**: In inclined faults, the hanging wall is the block above the fault plane and the footwall is below.

21.2 Causes of Faulting

Faults develop due to:

1. **Tectonic Stresses**: Generated by movements of lithospheric plates.
2. **Volcanic Activity**: Creates tension and displacement in rocks.
3. **Crustal Loading and Unloading**: Due to glaciers, sediments, or erosion.
4. **Human Activities**: Reservoir impoundment, mining, and oil extraction.

These stresses result in brittle failure of rocks, leading to fault formation and seismic energy release.

21.3 Classification of Faults

Faults are classified based on the relative motion of rock masses and the orientation of the fault plane.

21.3.1 Based on Direction of Displacement

a. ***Dip-Slip Faults***

Movement is predominantly vertical along the dip of the fault plane.

- **Normal Fault**: Hanging wall moves downward relative to the footwall due to extensional forces. Common in divergent plate boundaries.
- **Reverse Fault**: Hanging wall moves upward relative to the footwall due to compressive forces. Often found in convergent zones.
- **Thrust Fault**: A low-angle reverse fault (dip < 45°). Causes large-scale crustal shortening.

b. ***Strike-Slip Faults***

Movement is primarily horizontal along the strike of the fault plane.

- **Right-Lateral (Dextral)**: Opposite block appears to move to the right.
- **Left-Lateral (Sinistral)**: Opposite block appears to move to the left.

c. ***Oblique-Slip Faults***

Movement occurs both vertically and horizontally. This is a combination of dip-slip and strike-slip displacements.

21.4 Fault Geometry and Terminology

Understanding fault geometry is crucial for interpreting fault behavior and seismic potential.

- **Strike**: Direction of the line formed by the intersection of a fault plane with a horizontal surface.

- **Dip**: Angle between the fault plane and a horizontal surface, measured perpendicular to the strike.
- **Slip**: The relative displacement across a fault.
- **Fault Trace**: The line where a fault intersects the Earth's surface.
- **Fault Zone**: A region with multiple closely spaced faults.

21.5 Fault Mechanics and Stress Analysis

The behavior of faults under stress is analyzed using the **Mohr-Coulomb failure criterion**:

$$\tau = c + \sigma n \times \tan(\phi)$$

Where:

- τ = shear stress
- c = cohesion
- σn = normal stress
- ϕ = angle of internal friction

When shear stress exceeds the rock strength, faulting occurs. Stress accumulation over time results in elastic deformation, eventually released as seismic energy during fault rupture.

21.6 Active, Inactive, and Reactivated Faults

Active Faults

- Recently moved (within Holocene epoch, ~11,700 years).
- High potential for future earthquakes.
- Must be identified and considered in site selection and zoning.

Inactive Faults

- No movement in recent geological history.
- Often considered dormant, but may still reactivate under stress.

Reactivated Faults

- Previously inactive faults reactivated by new tectonic stress.
- Common in intraplate regions due to lithospheric adjustments.

21.7 Mapping and Identification of Faults

Techniques used:

1. **Geological Mapping**: Surface features and rock displacements.
2. **Remote Sensing and Aerial Photography**: Linear features, offset rivers, fault scarps.
3. **Seismological Studies**: Epicenter alignment and seismic reflection.
4. **Geophysical Surveys**: Gravity, magnetic, and resistivity methods.
5. **Trenching and Paleoseismology**: Dating past fault movements.

21.8 Faults and Earthquake Generation

Faults act as zones of weakness where stress accumulates. Earthquake mechanisms include:

- **Elastic Rebound Theory**: Stress builds up until rocks rupture and "snap back," releasing energy.
- **Seismic Moment (M_0)**: $M_0 = \mu \times A \times D$ Where μ = rigidity modulus, A = fault area, D = displacement.

Larger faults tend to produce higher magnitude earthquakes. Fault rupture length and slip displacement are directly related to seismic magnitude.

21.9 Fault Hazard Assessment and Risk Mitigation

Civil engineers assess fault-related seismic risk through:

1. **Fault Avoidance Zoning**: Setback distances from known fault lines.
2. **Microzonation Studies**: Identify seismic risk variations across regions.
3. **Building Codes**: Design structures for expected ground shaking.
4. **Lifeline Safety Planning**: Ensuring stability of bridges, pipelines, etc., crossing faults.

21.10 Important Fault Systems in India

1. **Himalayan Frontal Thrust (HFT)** – Major active thrust zone; highly seismic.

2. **Main Boundary Thrust (MBT)** – Generates large earthquakes in the Himalayas.
3. **Main Central Thrust (MCT)** – Deep-seated and active.
4. **Narmada-Son Lineament (NSL)** – Intraplate faults in Central India.
5. **Western Ghats Faults** – Associated with seismic activity in Peninsular India.

These fault zones are crucial for national seismic hazard mapping.

21.11 Engineering Implications of Faults

- **Foundation Design**: Fault activity influences bearing capacity and liquefaction potential.
- **Tunnel Alignment**: Avoidance of active fault zones is recommended.
- **Dams and Reservoirs**: Require extensive fault investigations to avoid induced seismicity.
- **Transportation Infrastructure**: Bridges and highways must be designed for differential movement across faults.

Certainly. Here's the continuation of **Chapter 21: Geological Faults**, with **additional key topics** added **after Section 21.11**, maintaining the technical depth and logical flow suited for a BTech Civil Engineering elective course in *Earthquake Engineering*.

21.12 Fault Rupture Propagation and Seismic Waves

When a fault ruptures, seismic energy is released and travels through the Earth in the form of waves. The nature of this rupture significantly affects ground motion intensity.

- **Nucleation Point**: The initial point of rupture.
- **Rupture Front**: The propagating crack edge along the fault.
- **Directional Rupture Effects (Directivity)**: When rupture propagates in the same direction as the wave front, seismic waves may be amplified in that direction.
- **Slip Distribution**: Varies along the fault; zones of high slip can cause severe ground shaking.

- **Asperities**: Rough patches on faults that temporarily lock movement; their failure often results in high-magnitude events.

Types of Waves Generated:

- **P-waves** (Primary): Compressional, travel fastest.
- **S-waves** (Secondary): Shear waves, cause structural damage.
- **Surface Waves** (Love and Rayleigh): Travel along the crust; typically cause the most destruction during shallow earthquakes.

21.13 Fault Creep and Locked Faults

Fault Creep

Some faults slide slowly without causing significant earthquakes. This slow, aseismic slip is known as **fault creep**.

- Observed in parts of the **San Andreas Fault (California)**.
- Creep reduces the stress accumulation but may still damage infrastructure through gradual deformation.

Locked Faults

- Faults that do not move even under accumulating stress.
- These can store large amounts of elastic strain energy.
- Sudden rupture results in **great earthquakes** (e.g., 2004 Sumatra-Andaman earthquake).

21.14 Fault-Induced Ground Deformations

Active faulting can cause permanent surface deformation, which civil engineers must account for.

- **Vertical Displacement**: Can tilt buildings and disturb drainage.
- **Lateral Offsets**: Roads, pipelines, and rails can shear apart.
- **Ground Fissures**: Cracks at the surface near fault ruptures.
- **Warping and Folding**: Often near thrust faults or blind faults.

Such deformation is irreversible and can occur instantly during seismic events.

21.15 Blind Faults and Hidden Seismic Sources

Blind Faults

- Do not rupture the surface.
- Can only be detected via subsurface imaging techniques (e.g., seismic reflection profiling).

These faults are especially dangerous in urban regions, where their presence may remain unknown until an earthquake occurs.

Buried Ruptures

- Rupture initiates below ground, producing strong ground motion without visible surface faulting.
- Common in sedimentary basins.

21.16 Faults and Soil-Structure Interaction

Fault-induced ground motions interact with soil and structure systems:

- **Soft Soil Amplification**: Seismic waves amplify in soft, unconsolidated soils near faults.
- **Differential Movement**: When a structure spans a fault zone, different parts may move out of phase.
- **Foundation Uplift or Settlement**: Unequal fault displacements cause permanent structural tilting or collapse.

Modern building codes integrate soil-fault-structure interaction models to enhance resilience.

21.17 Instrumentation and Monitoring of Fault Activity

Monitoring active faults is essential for early warning systems and hazard mitigation.

Instruments Used:

- **GPS Stations**: Detect crustal deformation with millimeter precision.
- **Seismographs**: Record ground motion.
- **Strainmeters and Tiltmeters**: Measure stress and tilt across fault planes.

- **InSAR (Interferometric Synthetic Aperture Radar)**: Satellite-based imaging for detecting surface movement.

Real-Time Fault Monitoring

Active faults in India (e.g., Himalayas, Kachchh) are now monitored by institutions like the **National Centre for Seismology (NCS)**.

21.18 Engineering Case Studies Involving Faults

1. **Bhuj Earthquake (2001)**
   - Fault: Kachchh Mainland Fault
   - Result: Surface rupture, 7.7 Mw, massive infrastructure loss.
2. **San Fernando Earthquake (1971)**
   - Thrust faulting caused damage to lifelines and hospitals.
3. **Chi-Chi Earthquake, Taiwan (1999)**
   - Chelungpu Fault ruptured surface; displacement up to 8 m.
4. **Japan Tōhoku Earthquake (2011)**
   - Subduction faulting; devastating tsunami.

These cases emphasize the importance of incorporating fault data into urban and infrastructure planning.

21.19 Guidelines for Civil Engineers Regarding Fault Zones

Civil engineers must consider faults during:

- **Site Selection**: Avoid building on or near active faults.
- **Seismic Microzonation**: Account for fault-induced amplification.
- **Bridge and Tunnel Design**: Design for fault displacement tolerance.
- **Dam Design**: Locate away from major fault rupture zones.
- **Zoning Laws and Setbacks**: Enforce minimum fault clearance (e.g., Alquist-Priolo Act in California mandates setbacks from active faults).

IS codes (e.g., IS 1893) and global standards require incorporating fault hazard assessment in design.