Chapter 37: Effect of Soil Properties and Damping – Liquefaction of Soils

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Introduction

During an earthquake, the behavior of soil plays a critical role in determining the performance and stability of structures. Among the most alarming consequences of seismic activity in loose, saturated soils is **liquefaction** — a phenomenon wherein the soil temporarily behaves like a fluid, losing its shear strength and stiffness. The susceptibility of soil to liquefaction and the severity of its effects are influenced by several intrinsic soil properties as well as external dynamic loading characteristics such as damping and cyclic loading.

This chapter explores the detailed mechanics behind soil behavior during dynamic loading, focusing on **how various soil properties and damping characteristics influence the occurrence and effects of liquefaction**.

37.1 Soil Properties Affecting Dynamic Behavior

Soil behavior under seismic loading depends greatly on its physical and mechanical properties. Key parameters include:

37.1.1 Grain Size Distribution

- **Sands and silts** with a uniform grain size are more susceptible to liquefaction.
- Well-graded soils offer more resistance due to tighter packing.
- **Fine-grained soils** (e.g., clays) typically do not liquefy unless they exhibit **low plasticity**.

37.1.2 Relative Density

- Loose sands (low relative density) are highly prone to liquefaction.
- Densification through compaction significantly increases resistance to liquefaction.

37.1.3 Permeability

- Influences the rate at which pore water pressures dissipate.
- Low-permeability soils trap water pressure, increasing liquefaction potential.

37.1.4 Void Ratio

- High void ratio indicates loose packing and high susceptibility to volume change under cyclic loading.
- Soils with high void ratios are more prone to **pore pressure build-up**, which triggers liquefaction.

37.1.5 Plasticity Index (PI)

- Clays with PI > 12 generally exhibit good resistance to liquefaction.
- Soils with low PI (non-plastic or slightly plastic silts) are more vulnerable.

37.1.6 Saturation

- **Full saturation (Sr ≈ 100%)** is a critical requirement for liquefaction.
- Partial saturation allows drainage and reduces the risk of pore pressure build-up.

37.1.7 Soil Fabric and Structure

- Natural cementation or structured soils may initially resist liquefaction but may collapse suddenly once bonds are broken.
- Remolded soils are more susceptible.

37.2 Stress-Strain Behavior of Soils under Cyclic Loading

When subjected to repeated seismic shaking, soils experience:

37.2.1 Hysteresis Loops

- Cyclic stress-strain curves show energy dissipation.
- Area inside the loop represents **damping** capacity.
- Loose soils show larger loops (more damping) but lower strength.

37.2.2 Degradation of Shear Modulus

- **Shear modulus (G)** decreases with increased cyclic strain.
- Dynamic modulus curves (G/G_max vs. shear strain) are used to model this.

37.2.3 Build-up of Excess Pore Water Pressure

- Occurs due to cyclic loading in undrained conditions.
- Leads to progressive reduction in effective stress, potentially to zero (liquefaction).

37.3 Damping in Soils

Damping refers to the ability of the soil to dissipate energy during dynamic or cyclic loading.

37.3.1 Types of Damping

- **Material damping** (due to internal friction).
- **Radiation damping** (energy lost to surrounding media).
- **Viscous damping** (assumed in analytical models).

37.3.2 Damping Ratio (ξ)

- Defined as the ratio of energy dissipated per cycle to the maximum strain energy.
- Typical damping ratios:
  - Dry sand: 1–2%
  - Saturated sand: 2–5%
  - Soft clay: up to 10%

37.3.3 Factors Affecting Damping

- Strain level: Damping increases with strain.
- Soil type and density.
- Frequency of loading.
- Hysteretic behavior.

37.4 Liquefaction of Soils

Liquefaction is a condition wherein soil temporarily loses its shear strength due to excess pore water pressure generated by cyclic loading.

37.4.1 Mechanism of Liquefaction

- Rapid undrained loading → excess pore water pressure builds up.
- Effective stress decreases → shear strength approaches zero.

- Soil behaves like a **viscous liquid**, causing ground failures.

37.4.2 Conditions Necessary for Liquefaction

1. Loose, cohesionless soil (e.g., silty sand).
2. Saturation (water table near surface).
3. Cyclic or dynamic loading (e.g., earthquake).
4. Rapid loading preventing drainage.

37.4.3 Types of Liquefaction

- **Flow Liquefaction**: Occurs when shear stress exceeds static shear strength.
- **Cyclic Liquefaction**: Repeated cycles cause progressive build-up of pore pressure.
- **Ground Oscillation**: Upper layers lose strength, causing surface oscillations.
- **Lateral Spreading**: Ground slides laterally due to loss of shear strength.

37.5 Factors Influencing Liquefaction Potential

37.5.1 Seismic Factors

- Earthquake magnitude and duration.
- Peak ground acceleration (PGA).
- Number of strong motion cycles.

37.5.2 Soil Factors

- Grain characteristics and fines content.
- Relative density.
- Initial effective stress.
- Confining pressure.

37.5.3 Groundwater Table

- Depth to water table is critical; shallow groundwater increases liquefaction potential.

37.6 Evaluation of Liquefaction Potential

Several methods are used for assessing the liquefaction potential of a site:

37.6.1 Field Tests

- **Standard Penetration Test (SPT)**: Most common method.
  - Corrected N-values used with empirical curves.
- **Cone Penetration Test (CPT)**: Measures tip resistance and sleeve friction.
- **Shear Wave Velocity (Vs)**: Stiffer soils are less likely to liquefy.

37.6.2 Empirical Procedures

- Based on Seed and Idriss (1971) methodology.
- Factor of Safety (FS) = **Cyclic Resistance Ratio (CRR)** / **Cyclic Stress Ratio (CSR)**
  - FS < 1 → Liquefaction likely.

37.6.3 Laboratory Testing

- Cyclic triaxial tests.
- Cyclic simple shear tests.
- Undrained loading tests to observe pore pressure build-up.

37.7 Effects of Liquefaction

The consequences of liquefaction can be severe:

- Settlement of ground and structures.
- Tilting or overturning of buildings.
- Lateral spreading and flow failures.
- Sand boils and ground fissures.
- Damage to lifelines (pipelines, roads, bridges).
- Bearing capacity failure.

37.8 Mitigation of Liquefaction Hazards

Preventive measures are essential for structures in liquefiable zones.

37.8.1 Ground Improvement Techniques

- **Densification**: Vibro-compaction, dynamic compaction.
- **Grouting**: Chemical or cement-based to reduce permeability.

- **Drainage**: Prefabricated vertical drains (PVDs), gravel drains.
- **Reinforcement**: Use of geosynthetics or stone columns.

37.8.2 Structural Solutions

- Deep foundations to bypass liquefiable layers.
- Raft foundations to spread loads.
- Base isolation and energy dissipation devices.

37.9 Residual Strength after Liquefaction

Once liquefaction occurs and pore pressures dissipate, the soil does not necessarily regain its original strength immediately. The **residual strength** is the remaining shear strength of the soil after liquefaction has occurred.

37.9.1 Definition and Importance

- Residual strength is critical in evaluating **post-liquefaction stability** of slopes, embankments, and foundations.
- Often much lower than pre-liquefaction strength.

37.9.2 Factors Affecting Residual Strength

- Soil type and grading (uniform sands have lower residual strength).
- Void ratio and fabric after reconsolidation.
- Degree of strain or deformation during liquefaction.
- Confining pressure and effective stress.

37.9.3 Measurement

- Laboratory: Ring shear tests, cyclic triaxial tests under undrained conditions.
- Field observations: Back-analysis of case histories (e.g., flow slides).

37.10 Post-Liquefaction Behavior of Soils

Understanding soil behavior after liquefaction is crucial for the safe design of infrastructures in seismic zones.

37.10.1 Reconsolidation and Settlement

- As excess pore pressures dissipate, reconsolidation occurs.
- **Significant settlement** can take place, particularly in loose, saturated fills.

37.10.2 Lateral Displacement

- Flow slides and lateral spreads are common in post-liquefaction conditions.
- Structures built on such soils may **tilt or displace horizontally.**

37.10.3 Rebuilding Shear Strength

- Soil may **regain part of its strength** through reconsolidation.
- But original structure/fabric is often lost, leading to different engineering properties.

37.11 Case Studies on Liquefaction

Historical case studies provide invaluable insights into the real-world consequences of liquefaction.

37.11.1 Niigata Earthquake, Japan (1964)

- Severe liquefaction of sandy soils caused **tilting of apartment buildings**.
- Extensive sand boils and settlements observed.

37.11.2 Alaska Earthquake (1964)

- Port of Anchorage experienced **massive ground failures** due to liquefaction.
- Large-scale lateral spreading destroyed port facilities.

37.11.3 Bhuj Earthquake, India (2001)

- Liquefaction-induced **ground cracking and settlement** observed in Kachchh region.
- Bridges and culverts experienced damage due to lateral spreads.

37.11.4 Christchurch Earthquakes, New Zealand (2010–2011)

- Widespread liquefaction in residential zones.
- **Economic damage** due to ground loss and infrastructure failures.

37.12 Recent Advances in Liquefaction Assessment

New technologies and research are continuously improving liquefaction prediction and mitigation strategies.

37.12.1 Advanced Site Characterization

- Use of **seismic CPT** and **downhole Vs profiling**.
- LiDAR and satellite-based **InSAR** to detect surface deformation.

37.12.2 Numerical Modeling

- Use of finite element and finite difference methods.
- Coupled **flow-deformation models** for better simulation.

37.12.3 Machine Learning Applications

- AI/ML models trained on historical data for liquefaction prediction.
- Inputs: SPT/CPT data, earthquake parameters, soil types, etc.

37.13 Codal Provisions and Guidelines

National and international codes provide guidelines for evaluating and mitigating liquefaction.

37.13.1 IS Codes (India)

- **IS 1893 (Part 1): 2016** – General provisions for seismic design.
- **IS 1893 (Part 2): 2023** – Recommendations for liquefaction evaluation in dams and foundations.

37.13.2 International Standards

- **NEHRP (USA)** – Detailed guidelines on cyclic stress approach.
- **Eurocode 8** – Considerations for liquefaction in seismic design.
- **Japanese Code** – Uses shear wave velocity-based assessments.

37.13.3 Design Recommendations

- Apply safety factors (FS > 1.1–1.3).
- Ensure site-specific studies for critical infrastructure.
