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DYNAMIC RESPONSE OF SANDY SOIL UNDER CYCLIC LOADING: A COMPREHENSIVE REVIEW

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Abstract Understanding the dynamic response of sandy soil under cyclic loading is essential for the safe design of foundations, offshore structures, machine foundations, and earthquake-resistant infrastructure. Sandy soils exhibit complex behaviors—such as stiffness degradation, excess pore pressure development, shear strain accumulation, and liquefaction susceptibility—when subjected to repetitive or oscillatory loads. This review synthesizes theoretical, experimental, and numerical findings published over the past three decades to present a comprehensive understanding of cyclic stress–strain behavior, influencing factors, constitutive modeling, and mitigation measures. Emphasis is placed on the effects of relative density, fines content, confining pressure, loading amplitude, number of cycles, drainage conditions, and fabric anisotropy on dynamic soil response. Laboratory data from cyclic triaxial tests, resonant column tests, and simple shear tests are analyzed to understand small-strain stiffness, modulus reduction curves, and damping ratios. Recent advances in DEM simulations, finite element modeling, and dynamic soil improvement techniques such as cementation, bio-cementation, and fiber reinforcement are also examined. The review concludes that although significant progress has been made, predicting long-term cyclic behavior of sandy soils under complex loading paths remains a challenge, necessitating multidisciplinary approaches that integrate micro-mechanics, advanced numerical modeling, and field-scale observations.

Keywords:

Cyclic loading, Sandy soil, Dynamic response, Liquefaction, Modulus degradation, Damping ratio, Cyclic triaxial test, Dynamic soil behavior, Excess pore pressure, Soil improvement.

1. Introduction

Sandy soils are widely encountered in geotechnical engineering projects such as high-rise buildings, offshore wind turbine foundations, railway embankments, machine foundations, and

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seismic zones. Their lack of inherent cohesion and contractive nature under undrained cyclic loading make them highly sensitive to dynamic stresses. Engineers must anticipate behavioral patterns such as modulus decay, cyclic mobility, strain softening, pore pressure buildup, and liquefaction to ensure structural safety (Seed & Idriss, 1971). The demand for resilient infrastructure has intensified research focus on the dynamic behavior of sandy soils under varying conditions of stress amplitude, strain ranges, cyclic frequency, and environmental constraints.

The increasing occurrence of seismic events globally has further emphasized the need to understand the long-term cyclic degradation characteristics of sandy soils. When soils experience repeated shear stresses—such as those generated by earthquakes, waves, rotating machinery, or traffic—their behavior deviates significantly from static responses, producing unpredictable structural consequences (Vucetic & Dobry, 1991). Thus, this review aims to synthesize current knowledge and highlight key parameters that govern the cyclic response of sands.

2. Mechanisms Governing Dynamic Behavior of Sandy Soil

Sandy soil subjected to cyclic loading encounters various mechanisms that control its mechanical response. The key mechanisms include:

2.1 Stress–strain hysteresis: Under dynamic loads, the soil follows a nonlinear hysteretic stress–strain relationship, where stiffness reduces with strain amplitude (Hardin & Drnevich, 1972).

2.2 Energy dissipation: Energy is dissipated through internal friction, inter-particle sliding, and rearrangement of grains, linked to the damping ratio.

2.3 Pore pressure buildup: Undrained cyclic loading causes progressive pore water pressure accumulation, reducing effective stress and promoting liquefaction (Seed et al., 1983).

2.4 Cyclic mobility: Even before liquefaction, sands show temporary loss of strength due to strain accumulation per cycle (Castro, 1975).

2.5 Fabric evolution: Cyclic loading changes grain arrangement and void ratio, resulting in contractive or dilative behavior depending on density and confining stress (Lade, 1992).

These mechanisms interact to produce the complex response of sandy soil in cyclic environments.

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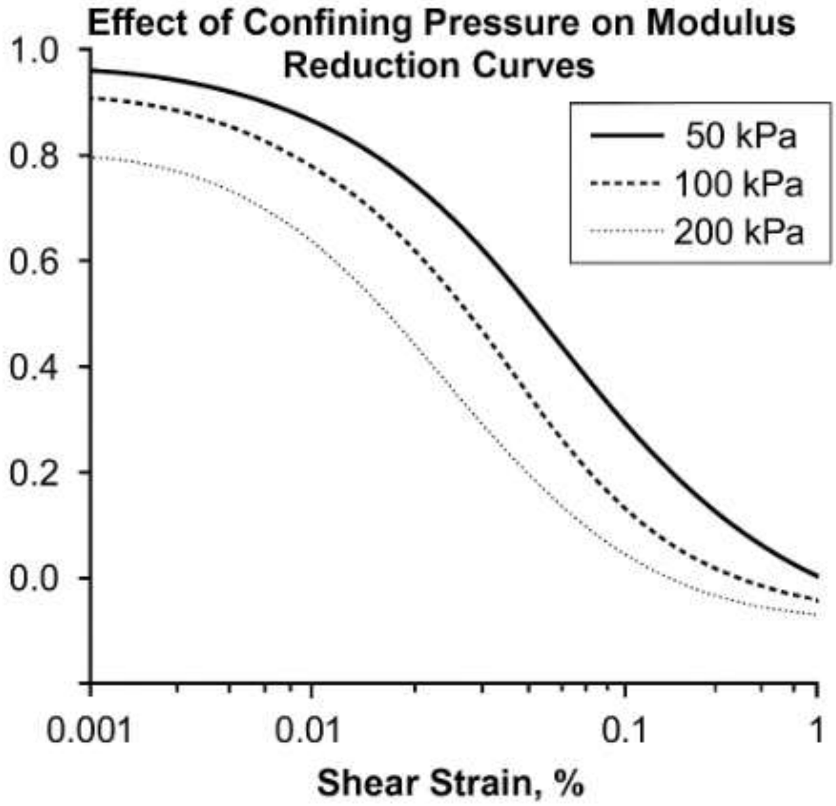

Figure 1- Effect of Confining Pressure on Modulus Reduction Curves

3. Factors Influencing Cyclic Behavior of Sandy Soil

3.1 Relative Density

Denser sands exhibit higher resistance to deformation and liquefaction because inter-granular forces and dilative tendencies are stronger (Ishihara, 1993). Loose sands, however, contract rapidly and reach pore pressure ratios close to liquefaction thresholds.

3.2 Confining Pressure

Higher confining pressure increases small-strain stiffness and reduces the likelihood of liquefaction (Kramer, 1996). Low confining pressures allow rapid pore pressure accumulation.

3.3 Cyclic Stress Ratio (CSR)

CSR determines the severity of cyclic loads. A higher CSR causes faster modulus degradation and pore pressure rise (Seed et al., 1983).

3.4 Number of Cycles

Dynamic response is cumulative. Small CSR may cause failure after many cycles, a phenomenon known as cyclic fatigue, widely observed in sands (Dobry et al., 1982).

3.5 Fines Content

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Silty sands exhibit a mixture of contractive and dilative tendencies depending on fines percentage and plasticity (Thevanayagam, 1998).

3.6 Drainage Conditions

Partially drained conditions alter the rate of pore pressure change and cyclic mobility.

3.7 Grain Shape and Mineralogy

Angular sands provide higher shear resistance compared to spherical grains due to interlocking (Cho et al., 2006).

Table 1: Major Parameters Influencing Cyclic Behavior of Sandy Soils

Parameter	Effect on Dynamic Behavior
Relative Density	Higher density → increased stiffness and liquefaction resistance
Confining Pressure	Higher pressure → reduced pore pressure buildup
CSR	Higher CSR → faster modulus degradation
Fines Content	Moderate fines may increase mobility; excess fines reduce drainage
Number of Cycles	Accumulated strain and fatigue failure
Grain Shape	Angularity increases interlocking and stiffness

4. Laboratory Methods for Evaluating Dynamic Response

4.1 Cyclic Triaxial Test

One of the most widely used methods, cyclic triaxial testing provides insights into stress–strain loops, pore pressure generation, and cyclic resistance ratios (ASTM D5311).

4.2 Resonant Column Test

Examines **small-strain shear modulus (Gmax)** and **damping ratio** using steady-state vibration; valuable for seismic site response analysis (Hardin & Richart, 1963).

4.3 Cyclic Simple Shear Test

Replicates horizontal shear stresses closer to real earthquake loading. It allows control of stress paths and is essential for liquefaction research (Bjerrum & Landva, 1966).

4.4 Bender Element Tests

Used to measure shear wave velocity in soil samples without disturbing the specimen, providing high-resolution small-strain modulus data.

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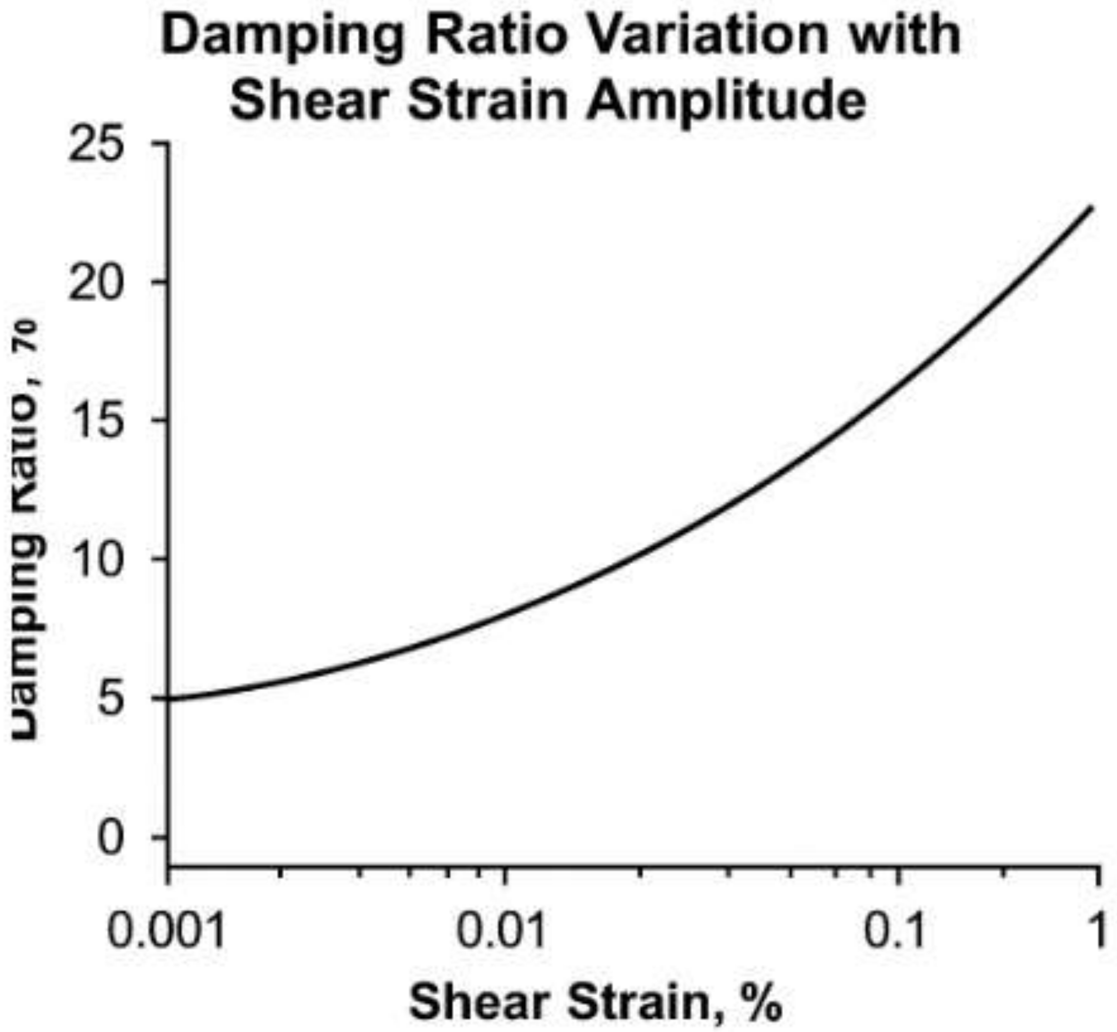

Figure 2 Damping Ratio Variation with Shear Strain Amplitude

5. Dynamic Properties of Sandy Soil

5.1 Shear Modulus Degradation

Sandy soils exhibit stiffness reduction with increased shear strain. Modulus reduction curves (G/Gmax) describe the relationship and are used in seismic site response models (Vucetic & Dobry, 1991).

5.2 Damping Ratio

Damping increases with cyclic strain amplitude because more energy is dissipated through inter-particle sliding. Resonant column and cyclic triaxial tests quantify damping values (Hardin & Drnevich, 1972).

5.3 Excess Pore Pressure Ratio (ru)

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The buildup of pore pressure is central to liquefaction prediction. Models by Seed et al. (1983) and Martin et al. (1975) remain widely applied.

5.4 Cyclic Resistance Ratio (CRR)

Represents the soil's ability to withstand cyclic loading without liquefaction. CRR depends on density, fines, confining pressure, and stress history.

6. Liquefaction Behavior of Sandy Soil

Liquefaction occurs when the effective stress approaches zero due to persistent pore pressure buildup. Major causes include:

- Earthquake shaking
- Wave loading on offshore structures
- Rapid cyclic traffic loads

6.1 Liquefaction Triggering

Evaluated through CSR-CRR comparison. Numerous field case histories (e.g., Niigata 1964, Kobe 1995) form the basis of empirical curves (Youd et al., 2001).

6.2 Cyclic Mobility

Occurs before full liquefaction, as sands temporarily lose shear resistance but recover after pore pressure dissipation.

Table 2: Comparison of Liquefaction and Cyclic Mobility Characteristics

Feature	**Liquefaction**	**Cyclic Mobility**
Effective Stress	Reduces to near-zero	Reduces temporarily
Strength Loss	Severe and sudden	Gradual, recoverable
Pore Pressure	Ru ≈ 1.0	Ru < 1.0
Typical Density	Loose to medium	Dense sands

7. Numerical and Micro-Mechanical Modeling

7.1 Finite Element Modeling (FEM)

Advanced constitutive models such as:

- PM4Sand (Boulanger & Ziotopoulou, 2017)
- UBCSAND
- Pastor–Zienkiewicz

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These models simulate complex cyclic behaviors including stress path dependency and pore pressure evolution.

7.2 Discrete Element Method (DEM)

DEM analyzes particle-scale interactions and grain rearrangement during cyclic loading (Cundall & Strack, 1979). It provides insights into fabric changes, contact forces, and micro-scale energy dissipation.

7.3 Hybrid Approaches

Combining DEM-FEM improves modeling accuracy for large-strain cyclic problems and liquefaction prediction.

8. Soil Improvement Techniques to Enhance Dynamic Performance

8.1 Vibro-Compaction and Densification

Increases relative density and reduces cyclic strain potential.

8.2 Cementation and Grouting

Improves stiffness and reduces pore pressure development (Mitchell, 1981).

8.3 Bio-Cementation (MICP)

Recent eco-friendly method using bacterial calcite precipitation to increase sand cohesion and cyclic resistance (DeJong et al., 2010).

8.4 Fiber Reinforcement

Polypropylene, coir, and glass fibers improve cyclic resistance by enhancing tensile bridging within sand (Yetimoglu & Salbas, 2003).

9. Discussion

The dynamic response of sandy soil under cyclic loading is influenced by complex interactions between soil fabric, loading characteristics, environmental conditions, and drainage constraints. Experimental studies confirm that relative density and confining pressure significantly improve cyclic resistance, whereas higher CSR and repeated cycles deteriorate soil structure rapidly. Numerical simulations have reached a high level of sophistication in replicating laboratory outcomes; however, field-scale heterogeneity remains a major challenge. Future research must integrate micro-mechanical modeling, machine learning prediction tools, and bio-inspired soil improvement methods to enhance engineering design predictions.

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10. Conclusion

This review demonstrates that sandy soils exhibit nonlinear, cumulative, and fabric-dependent behaviors under cyclic loading. Parameters such as density, fines content, confining pressure, CSR, and number of cycles play dominant roles in determining modulus degradation, pore pressure buildup, and liquefaction potential. Advanced testing methods, numerical simulations, and soil improvement technologies have significantly enhanced the understanding of cyclic behavior. However, predicting long-term, real-field dynamic response remains challenging due to soil variability, drainage conditions, and multi-directional loading paths. Continued interdisciplinary research is necessary to develop more robust constitutive models and sustainable soil improvement solutions.

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