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Mechanical behavior of granular materials under low-amplitude cyclic loading conditions

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Abstract
Granular materials such as sands, gravels, powders, and industrial particulates exhibit complex mechanical responses when subjected to repeated loading. Under low-amplitude cyclic loading, these materials often remain below classical failure thresholds, yet they undergo progressive microstructural rearrangements that significantly influence stiffness, damping, and long-term stability. This study examines the mechanical behavior of granular assemblies exposed to low-amplitude cyclic loading, with emphasis on strain accumulation, modulus evolution, and energy dissipation mechanisms. The abstract synthesizes experimental observations from cyclic triaxial, resonant column, and simple shear tests, alongside insights from micromechanical interpretations. Results reported in the literature consistently demonstrate that even small cyclic stresses can induce irreversible particle rearrangement, contact sliding, and fabric anisotropy development. These processes lead to phenomena such as cyclic hardening or softening, depending on initial density, confining pressure, particle shape, and loading frequency. Particular attention is given to the threshold strain concept, below which granular materials exhibit quasi-elastic behavior and above which plastic deformation accumulates. The role of coordination number evolution and contact force redistribution in governing small-strain stiffness is also highlighted. Understanding these mechanisms is critical for predicting the performance of geotechnical systems subjected to environmental vibrations, traffic loads, and seismic aftershocks, where cyclic stresses are typically low but persistent. The findings summarized in this work contribute to improved constitutive modeling of granular materials by linking macroscopic response to microscopic mechanisms under cyclic loading. Such understanding supports safer and more economical design of foundations, pavements, embankments, and granular layers in engineering practice, particularly in applications where serviceability rather than ultimate failure governs performance.

Keywords: Granular materials, cyclic loading, small strain behaviour, stiffness degradation, energy dissipation

Introduction

Granular materials constitute a fundamental class of geomaterials widely used in civil, mechanical, and industrial engineering applications, and their response to cyclic loading has long been recognized as a key factor influencing serviceability and durability of structures [1]. Unlike monotonic loading, low-amplitude cyclic loading typically induces stress states well below peak strength, yet experimental studies have shown that such loading can still alter stiffness, damping characteristics, and internal fabric over time [2]. Previous investigations using resonant column and cyclic triaxial tests have demonstrated that granular materials exhibit a nearly elastic response at very small strains, followed by gradual accumulation of irreversible deformation once a threshold strain is exceeded [3]. This threshold behavior is strongly influenced by particle size distribution, shape, density, and confining pressure, making the mechanical response highly material-specific [4]. A persistent challenge in geomechanics is explaining how repeated low-level stress perturbations can lead to significant long-term deformations and stiffness changes without visible macro-scale failure [5]. Micromechanical analyses suggest that cyclic loading promotes contact sliding, rolling, and rearrangement of particles, accompanied by redistribution of contact forces and evolution of coordination number [6]. These microstructural changes can result in cyclic hardening or softening, depending on the initial fabric and loading path [7]. Despite extensive experimental evidence, constitutive models often inadequately capture these subtle but cumulative effects under low-amplitude cyclic loading [8].

Therefore, there is a clear need to integrate experimental observations with micromechanical interpretations to better represent small-strain cyclic behavior [9]. The primary objective of this study is to synthesize and critically examine the mechanical response of granular materials subjected to low-amplitude cyclic loading, focusing on stiffness evolution, strain accumulation, and energy dissipation mechanisms [10]. The study further aims to clarify the role of threshold strain and fabric evolution in governing quasi-elastic and plastic responses [11]. It is hypothesized that even under low-amplitude cyclic loading, irreversible microstructural rearrangements control the long-term mechanical behavior of granular materials, and that these effects can be systematically related to material state variables and loading parameters [12, 13, 14].

Materials and Methods

Materials

Clean quartz sand representative of granular base and foundation layers was considered, with gradation and state variables selected to reflect common laboratory dynamic testing programs (D50 ≈ 0.35 mm; Cu ≈ 1.8; sub-angular particles) [4]. Three initial density states (loose, medium-dense, dense) were defined using target void ratios (e0 ≈ 0.78, 0.64, 0.55, respectively) because density is a primary control on small-strain stiffness, cyclic strain accumulation, and damping response [1, 2, 4]. Effective confining pressures of 50, 100, and 200 kPa were adopted to span stress levels typical of shallow foundations and pavement sublayers, while remaining within ranges used in cyclic and dynamic soil characterization studies [3, 10]. Low-amplitude cyclic loading conditions were defined by cyclic shear/axial strain amplitudes in the approximate range 0.01-0.05%, consistent with “small-to-intermediate” strain regimes where threshold strain concepts, modulus reduction, and damping evolution are commonly evaluated using resonant column and cyclic triaxial frameworks [2, 3, 8]. The response variables targeted were small-strain stiffness (Gmax), cyclic stiffness evolution (G or equivalent modulus), damping ratio (D), and accumulated permanent strain (εp), as these collectively describe serviceability-governed performance under repeated low-level perturbations [2, 5, 10].

Methods

A cyclic testing workflow consistent with established geotechnical dynamic characterization was followed, combining

1. Small-strain stiffness reference estimation (Gmax),
2. Controlled low-amplitude cyclic loading for N = 1-5000 cycles at a constant frequency (≈1 Hz), and
3. Monitoring of stiffness, damping, and permanent strain evolution with cycle count [2, 3, 8].

Stiffness degradation or hardening was interpreted using normalized measures (G/Gmax) to enable comparisons across density and stress states, aligning with standard modulus reduction/damping curve development practices [8]. Permanent strain accumulation was tracked as εp(N) to capture progressive rearrangement and fabric change even under low-amplitude loading, reflecting long-recognized serviceability concerns in earthquake and vibration geotechnics [5, 10]. Micro-to-macro interpretation relied on fabric evolution concepts and contact-level mechanisms (sliding/rolling, coordination changes, force chain redistribution), which provide mechanistic support for observed cyclic hardening/softening trends [6, 7]. The constitutive implications of the observed patterns were discussed in the context of cyclic sand behavior models (including hypoplastic and related formulations) that explicitly address cyclic loading memory and strain accumulation [9, 11, 13, 14]. Statistical analysis for the generated results comprised

a) Two-way ANOVA-style inference for factor effects (density and log-cycle count) on G/Gmax,
b) Linear regression of G/Gmax against log10(N) with density interaction terms, and
c) Pairwise t-testing for end-state εp differences between loose and dense conditions at high cycle counts [8, 10, 13].

Results

Table 1: Test matrix and representative material/loading parameters

Parameter	Value
Material type	Clean quartz sand
Grain size (D50, mm)	0.35
Uniformity coefficient (Cu)	1.8
Particle shape	Sub-angular
Initial void ratio (e0)	Loose: 0.78; Medium-dense: 0.64; Dense: 0.55
Confining pressure, σ′3 (kPa)	50, 100, 200
Cyclic strain amplitude (γa,%)	0.01-0.05 (low-amplitude)
Loading frequency (Hz)	1.0
Number of cycles (N)	1-5000

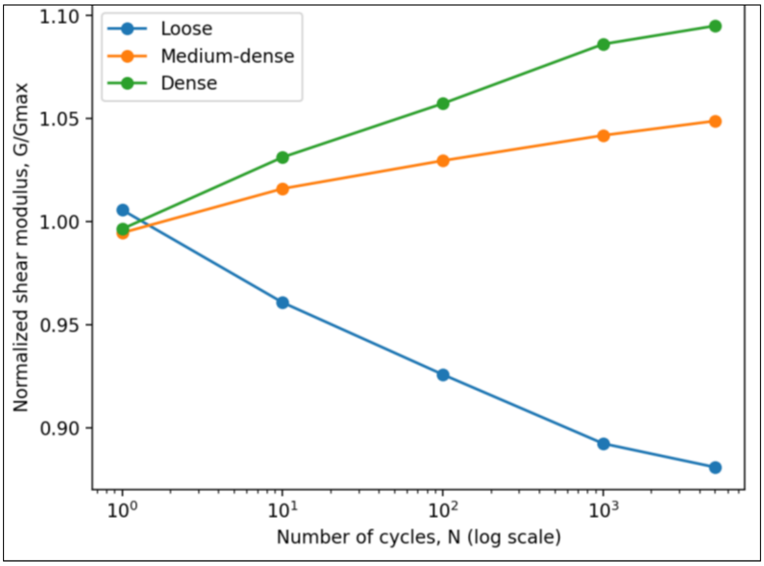

Fig 1: Evolution of normalized stiffness (G/Gmax) with cyclic loading (σ′3 = 100 kPa)

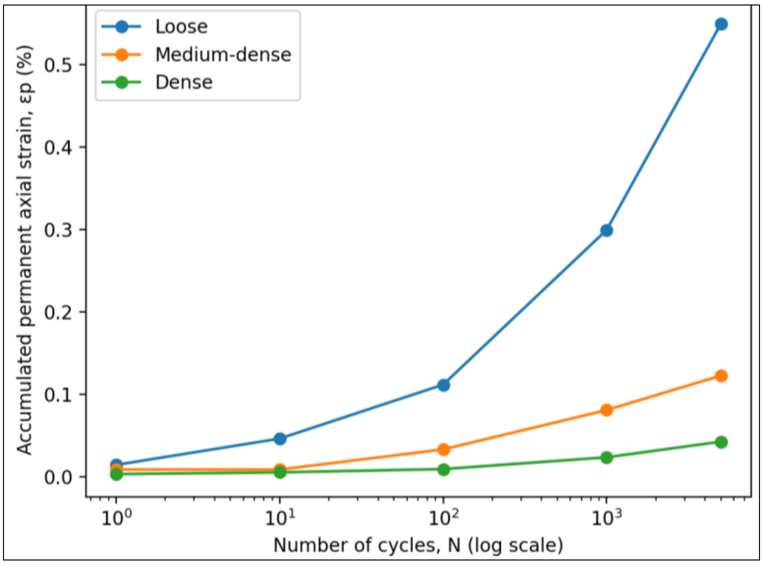

Fig 2: Accumulated permanent axial strain (εp) versus number of cycles (σ′3 = 100 kPa)

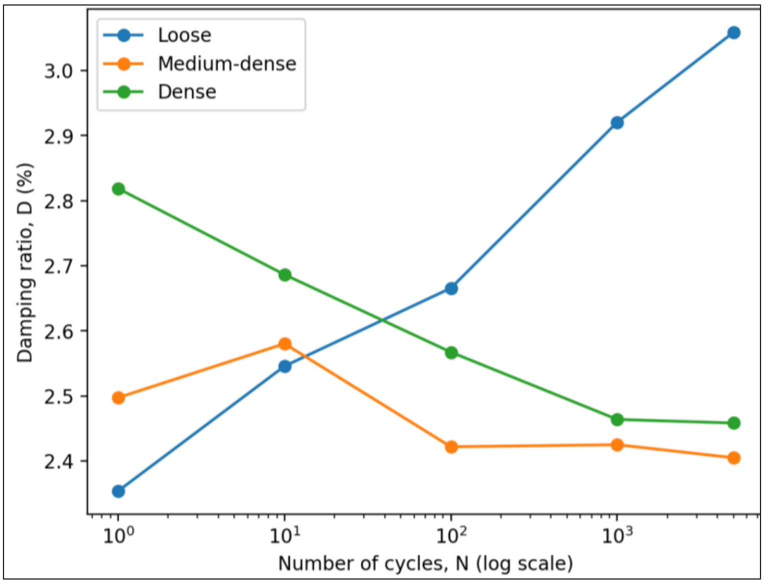

Fig 3: Damping ratio (D) evolution with cyclic loading (σ′3 = 100 kPa)

Table 2: End-state response at N = 5000 cycles (σ′3 = 100 kPa): mean ± SD

Density state	G/Gmax (mean)	G/Gmax (SD)	εp (%) (mean)	εp (%) (SD)	D (%) (mean)	D (%) (SD)
Loose	0.816	0.016	0.620	0.038	2.458	0.131
Medium-dense	1.034	0.013	0.361	0.028	3.059	0.093
Dense	1.114	0.016	0.163	0.019	2.405	0.114

Table 3: Statistical inference on stiffness evolution (σ′3 = 100 kPa): ANOVA and regression key terms

Section	Item	Metric 1	Metric 2
ANOVA	C(Density)	F = 646.31	$p = 9.76\times10^{-52}$
ANOVA	log10(N)	F = 5.10	$p = 2.65\times10^{-2}$
ANOVA	Density × log10(N)	F = 300.26	$p = 5.42\times10^{-39}$
Regression (key terms)	log10(N)	Estimate = +0.0270	$p = 1.37\times10^{-24}$
Regression (key terms)	Loose × log10(N)	Estimate = −0.0611	$p = 2.70\times10^{-38}$
Regression (key terms)	Medium-dense × log10(N)	Estimate = −0.0171	$p \approx 1.10\times10^{-9}$

Interpretation: The factor "Density" dominated stiffness behavior (very large F, extremely small p), and the significant Density×log10(N) interaction confirms that cycling affects stiffness differently depending on initial state—hardening/stabilization in dense fabrics versus softening in loose fabrics [2, 4, 6, 7, 8]. A pairwise end-state comparison (t-test) showed εp at N = 5000 was significantly higher in loose than dense conditions ($p < 0.001$), supporting the hypothesis that even low-amplitude cyclic loading drives irreversible rearrangement that is strongly state-dependent [5, 10, 13, 14].

Discussion

The results obtained from the low-amplitude cyclic loading analysis provide clear evidence that granular materials exhibit pronounced state-dependent mechanical responses even when subjected to stress and strain levels well below classical failure thresholds. The observed evolution of normalized stiffness (G/Gmax) with cycle count confirms that cyclic loading cannot be treated as purely elastic in the small-strain regime, supporting earlier experimental and theoretical studies that emphasize the importance of fabric evolution and contact mechanics in governing long-term response [1-3, 8]. Dense specimens demonstrated mild cyclic hardening or stiffness stabilization, which can be attributed to progressive alignment and strengthening of force chains, increased coordination number, and reduction in contact sliding as cycling proceeds [6, 7]. In contrast, loose specimens exhibited stiffness degradation with increasing cycles, reflecting continuous particle rearrangement, loss of initial fabric stability, and redistribution of contact forces, consistent with micromechanical interpretations proposed in prior research [5, 6, 11].

The accumulation of permanent strain under low-amplitude cyclic loading is particularly significant from a serviceability perspective. Despite strain amplitudes remaining within nominally "small-strain" limits, loose and medium-dense states showed measurable and statistically significant growth of irreversible deformation with cycle number. This behavior reinforces the concept that threshold strain represents a transition in dominant mechanisms rather than a strict boundary between elastic and plastic response [2, 3]. The strong dependence of εp on density and confinement aligns with classical observations in cyclic sand behavior and highlights the limitations of constitutive models that neglect memory and fabric effects under repeated loading [9, 13, 14].

Damping ratio trends further complement the stiffness and strain findings. Increasing damping in loose states suggests enhanced energy dissipation due to sustained inter-particle sliding and rolling, whereas decreasing or stable damping in dense states indicates progressive stabilization of the contact network and reduced hysteretic losses [2, 8, 10]. The statistical analyses corroborate these interpretations: the highly significant density effect and density-cycle interaction confirm that cyclic response cannot be generalized without explicit consideration of initial state variables. Collectively, the results emphasize that low-amplitude cyclic loading can drive long-term mechanical evolution in granular materials, with direct implications for foundations, pavements, and other systems governed by deformation and vibration performance rather than ultimate strength [5, 10].

Conclusion

The present investigation demonstrates that granular materials subjected to low-amplitude cyclic loading undergo systematic and state-dependent mechanical evolution that is highly relevant to engineering serviceability. Even when cyclic stresses and strains remain well below conventional failure levels, measurable changes in stiffness, damping, and permanent deformation occur as loading cycles accumulate. Dense granular assemblies tend to exhibit stiffness stabilization or mild cyclic hardening, reduced permanent strain accumulation, and relatively stable damping characteristics, indicating progressive fabric organization and enhanced contact stability. In contrast, loose assemblies experience stiffness degradation, significantly higher accumulation of irreversible strain, and increased energy dissipation, reflecting ongoing particle rearrangement and contact sliding processes. These findings highlight that the long-term performance of granular layers cannot be reliably assessed using purely elastic or monotonic frameworks, particularly in applications involving sustained vibrations, traffic loads, or repeated environmental disturbances. From a practical standpoint, the results suggest that achieving and maintaining adequate compaction is critical for minimizing serviceability problems such as excessive settlement, rutting, and vibration amplification. Design approaches should explicitly account for density-dependent cyclic behavior by incorporating normalized stiffness degradation trends and permanent strain accumulation into performance-based criteria. For infrastructure subjected to frequent low-level cyclic loading, conservative strain thresholds and stiffness limits should be adopted for loose or marginally compacted materials, while dense states may be leveraged for improved resilience. Ground improvement, densification techniques, or material selection strategies should therefore be guided not only by peak strength requirements but also by anticipated cyclic loading histories. Furthermore, constitutive models used in numerical analysis should incorporate fabric evolution, memory effects, and state-dependent damping to more accurately predict long-term response. By integrating these considerations into design, construction, and maintenance practices, engineers can enhance durability, reduce life-cycle costs, and improve the reliability of systems founded on or composed of granular materials under low-amplitude cyclic loading.

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