Hysteresis Behaviour and Energy Dissipation of Niger Delta Soil under Cyclic Loading Conditions

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ABSTRACT

The dynamic properties of soils influence seismic site response and liquefaction susceptibility. The previous studies mostly worked on effect of natural fiber and synthetic fiber used in clayey soil to investigate its effect on the dynamic properties of modified soil.This research deepens our understanding of the dynamic behaviour of Niger Delta soils, which is important for evaluating the region's vulnerability to liquefaction and seismic response. By combining experimental data with well-validated empirical models for small to medium-shear strain behaviour in the area's common sandy soils.This study experimentally investigated the behavior of damping ratio and shear modulus under the effects of confining pressure of sandy soils collected from Igbogene Town in the Niger Delta region of Nigeria. Undisturbed samples were acquired from boreholes using thin-walled tubes and consolidated anisotropically under effective stresses of 100, 200, 300, and 400kPa in a cyclic direct simple shear apparatus as per standards. Shear modulus reduction curves were generated from hysteretic stress-strain behavior at shear strains ranging from 0.001% to 2%. The data correlated well with empirical exponential decay models, validating their applicability for Niger Delta region soils. The damping ratio increased nonlinearly with strain, aligning with trends for liquefiable soils. Empirical equations tied the pressure-dependent damping behavior to existing models. Results provided input parameters for seismic ground response analyses. However, wider confining pressure testing would better characterize variability with depth. This work enhances geotechnical seismic hazard evaluations through validated empirical characterizations of small to medium-shear strain behavior for sandy deposits prevalent in the Niger Delta.The findings can be directly used in seismic ground response analysis. These results are expected to improve geotechnical seismic hazard assessments and provide more accurate evaluations of seismic risk in the region.

Keywords: Soil Dynamics; Shear Modulus; Damping Ratio; Confining Pressure; Liquefaction; Niger Delta

INTRODUCTION

The Niger Delta's complex geology presents unique challenges for soil mechanics, with Akpokodje [1] emphasizing the importance of understanding sub-soil behavior for loss estimation. The study's focus on soil hysteresis and energy dissipation under cyclic loads is particularly relevant given the region's seismic activity. Amini [2] demonstrated the noteworthy impact of confining pressure on dynamic soil characteristics, which aligns with this study's approach. The dynamic properties of soils, like damping ratio and shear modulus, are crucial parameters for evaluating site response during earthquakes [3]. Accurate characterization of these properties is essential for predicting liquefaction potential and seismic ground motions. While many empirical and semi-empirical models have been proposed [4], [5], site-specific measurements are still needed to validate and refine existing models for diverse geological environments.

In Nigeria, the Niger Delta region faces seismic hazards due to active faults, yet limited research has been conducted on the area's dynamic soil properties. This study addresses this gap by employing cyclic direct simple shear tests, following best practices [6], to provide valuable data for seismic hazard assessment. Undisturbed soil samples were acquired from boreholes representing various soil types in the Niger Delta. Anisotropic consolidation was applied under diverse confining pressures [3], followed by cyclic torsional shear tests to measure damping ratio and shear modulus at varying shear strain levels. Cyclic load-controlled triaxial tests were conducted at effective confining pressures of 100-400 kPa [7], with a damping ratio computed using Dobry et al.'s [8] equation. The study's findings on shear modulus reduction are consistent with established theories [9] and extend to Niger Delta soil types. The nonlinear damping ratio-strain relationship aligns with Głuchowski et al. [10] findings. Bender element tests [11] and resonant column tests offer comprehensive soil characterization [12].

The focus on sandy soils is particularly relevant, with Thevanayagam [13] highlighting the importance of fines content and confining stress. The study contributes to seismic risk understanding, supporting Anbazhagan et al.'s [14] emphasis on site classification. However, it could benefit from examining environmental implications, considering the oil and gas industry's presence [15].

To quantify the damping ratio, cyclic load-controlled triaxial tests were performed on the consolidated samples under undrained conditions at effective confining pressures (σ′c) of 100, 200, 300, and 400 kPa. At each strain level, four load cycles were applied with maximum shear strain (γ) ranging from 0.001% to 2% logarithmically. Using equation [Eq. 1] from Dobry et al.,[8] damping ratio (ξ) was computed by the developed hysteresis loop during each cycle.

$$\xi = (\Delta W/4\pi WE) \times 100 \tag{1}$$

During each loading cycle, ΔW is the energy dissipated and is equivalent to the area bounded by the hysteresis loop. WE is the energy dissipated during each loading cycle and can be derived from the maximum shear modulus of soil. Santos et al. [16] developed mathematical models to predict the variation in damping ratios for various soil types under variable confining pressures and shear stresses.

Shear modulus (G) was calculated by determining the stress-strain curve slope at each strain level for a given loading cycle.

$$G = \Delta\tau/\gamma. \tag{2}$$

Where Δτ denotes the change in shear stress and γ represents shear strain. The nonlinear relationship between shear modulus and strain, the data can be normalized using the maximum shear modulus (Gmax) measured at 0.001% strain. This normalization provided a clearer representation of the behavior of the shear modulus. The normalized shear modulus (G/Gmax) was then adjusted to match the empirical nonlinear curves introduced by Santos et al. [16]. The foundational equations for modeling how Gmax varies with effective confining pressure were established by Dobry et al. [8].

The soil behavior at any location can be assessed by accurately determining the dynamic soil properties such as shear modulus and damping ratio. The importance of these parameters can also be recognized as they help predict the liquefaction potential and seismic ground motion. Several empirical and semi-empirical models have been suggested [8], [16]to explain the variation of these properties with confining pressure and shear strain. Nonetheless, due to the significant inconsistency of soil conditions, site-specific data remains crucial for refining existing models and ensuring their applicability across diverse geological settings. Previously there are fewer studies on the dynamic soil characteristics of the Niger Delta region. The present data is insufficient to fully understand the variation of dynamic properties with depth and confining pressure. The Niger Delta region in Nigeria, characterized by active faults, is particularly vulnerable to earthquakes, yet a dearth of research exists on the dynamic soil properties of its soils. This research study focuses on obtaining undisturbed soil samples from Niger Delta and evaluating the dynamic properties of soil through cyclic torsional shear tests on consolidated samples. The ultimate goal of the study is to geotechnical seismic hazard assessments in Nigeria for the Niger Delta region by comparing the experimental data with the existing empirical models.

EXPERIMENT METHODOLOGY

Site Description and Sample Preparation

The study took place in Igbogene Town, Bayelsa State, Nigeria, positioned between longitudes 6°15′E and 6°45′E, and latitudes 4°45′N and 5°15′N. Igbogene Town lies within the Niger Delta, a region characterized by Tertiary and Quaternary clastic sediments, which have accumulated over millions of years through the deposition of materials carried by the Niger River. These sediments rest unevenly on a bedrock made up of Cretaceous sandstone and shale. The geological formations in the study area consist of intercalations of sand, silt, and clay deposited in fluvio-deltaic environments [17]. Specifically, Igbogene Town is underlain by sand and interlayered sand/silt/clay sediments of the Benin Formation, which covers most of the southern Niger Delta.

Testing Procedure

Undisturbed soil samples were collected from the site using thin-walled tube samplers with an outer diameter of 54 mm as per ASTM standard D1587. This sampling procedure preserves the natural on-field structure and properties of cohesive soils. Samples were extracted at the total depth intervals of 1.50 m from the ground surface down to a maximum depth of 30.0 m. Special precautions were taken during sampling and transportation to the laboratory to minimize sample disturbance. The samples were visually classified and representative samples were selected from each stratum for laboratory testing.

The site is underlain by a sequence of alternating sand, silt, and clay layers deposited in a fluvio-deltaic environment typical of the Niger Delta. The detailed stratigraphy was not well defined due to the sampling intervals. However, the soils can be broadly classified as silty soils, clayey soils, and sandy soils based on visual classification and index property testing. This variety of soil types prevalent at the site makes it suitable for investigating the effects of soil type and stress state on dynamic properties.

Experimental Setup

To perform the cyclic direct simple shear (DSS) test undisturbed soil samples were arranged to calculate the dynamic properties of soil. The DSS test was chosen due to its ability to subject soil samples to full reversal cyclic shear stresses and strains while maintaining constant normal stress, simulating field conditions during earthquakes.The DSS testing was performed as per American standards (ASTM D6528) using the bender element system for sample preparation and test execution. Bender elements consist of piezoceramic transducers that generate and detect shear waves to monitor the shear modulus continuously during the test. The samples were trimmed to a diameter of 50.0mm and a height of 20.0mm for testing. Porous stones and filter paper sheets were used at the top and bottom of the sample for drainage.

The samples were first consolidated anisotropically under the desired confining pressures of 100-400kPa with an increment of 100kPa, selected to represent overburden stresses at different depths. Confining pressure was applied using a triaxial cell while allowing only vertical drainage. The consolidation duration was 24 hours to allow complete dissipation of excess pore pressures.

After consolidation, the samples were subjected to cyclic shear loading under undrained conditions. The cyclic stress-controlled DSS testing consisted of single amplitude load cycles applied at a frequency of 0.10Hz. The shear stress amplitude was adjusted to achieve target shear strain amplitudes ranging from 10^{-4}% to 10^{-1}% in logarithmic increments. At each strain level, at least 10 cycles were applied until a stable response was achieved. The developed shear stresses and strains were recorded during testing to compute shear modulus and damping ratio. From the shear stress-strain hysteresis loop during the loading phase, the shear modulus was determined by calculating the secant modulus. Similarly, the energy dissipated within the loop represents the hysteresis energy used to quantify the damping ratio. Tests were terminated when the shear stress exceeded 0.1% to prevent sample failure. The output data of different shear strain levels were then utilized to develop the shear modulus reduction and damping ratio curves.

RESULTS AND DISCUSSION

This study considered the effect of confining pressure on the dynamic characteristics of soil in the region of the Nigerian Niger Delta using Bender Element (BE), and Resonant Column (RC) testing. Samples were prepared carefully to ensure consistency in initial conditions. The results show a good relationship between maximum shear modulus and confining pressure as studied by Dobry et al., [8]

$$G_{max} = G_{ref}\left({\sigma'_c}/{\sigma'_{ref}}\right)^k \qquad (3)$$

Where G_{ref} is the reference shear modulus at reference confining pressure σ'_{ref} and k is the soil-dependent exponent. All soil samples from the selected location exhibited the same behavior.

As expressed by the eq.[4] because of the proportional relationship between shear velocity (Vs) and shear modulus, the shear velocity increases with the rise in confining pressure.

$$V_s = \sqrt{G_{max}/\rho} \qquad (4)$$

where ρ is the soil's mass density.

The study observed that as confining pressure increased, the minimum damping ratio (Dmin) decreased, which aligns with previous research by Darendeli [18] and Santos et al. [16]. This is because higher confinement leads to stiffer soil, reducing its ability to dissipate energy. Empirical models developed in the study accurately captured the effects of confining pressure on Gmax, Vs, and Dmin for silt samples, making them useful for evaluating liquefaction potential and seismic analysis in the Niger Delta. Although this research focused on silt, further studies are needed to explore the dynamic properties of sand and clay in the region for a more comprehensive understanding of its seismic risks [17].

Impact of a Confining Pressure of 100 kPa on Shear Strain and Shear Modulus:

The effect of confining pressures on the dynamic response of sandy soils in Igbogene Town, Niger Delta was investigated. DSS tests were performed on undisturbed soil samples collected from boreholes in Igbogene Town under effective confining pressures (σ′c) of 100, 200, 300, and 400 kPa to represent pressure conditions at different depths.

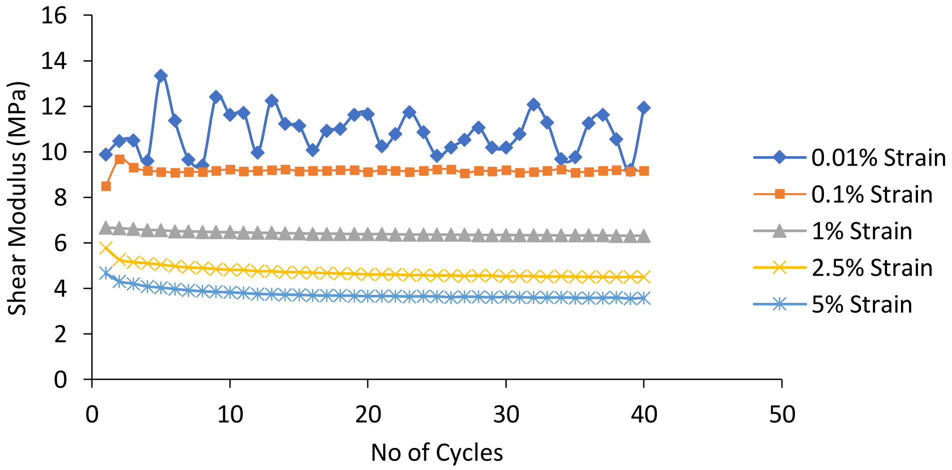

Fig. 1: Effect of 100kPa confining pressure on Shear Modulus

The discrepancy of normalized shear modulus $\frac{G}{G_{max}}$ with shear strain was determined from the stress-strain hysteresis loops developed during DSS testing as per ASTM D6528 standards. As shown in Figure 1 explains the decrease of shear modulus G with increasing shear strain for sandy soil subjected to a confining pressure of 100 kPa. At very small strains ($\gamma < 0.001\%$), G remained relatively constant. With further increase in strain, G reduced nonlinearly and followed an exponential decay trend consistent with the findings of Santos and Correia [16].

The data obtained at 100 kPa was fitted to existing empirical models by Santos et al. [4] to quantify the shear modulus reduction behavior. A good correlation was observed between the measured data and the model, validating its applicability for soils in the Niger Delta region under the studied stress condition as suggested for site-specific soils by Dobry et al. [8]. This confirms the impact of confining pressure and shear strain level on the shear modulus highlighted in previous studies.

The results provide valuable input for developing shear modulus reduction curves needed in dynamic analyses like liquefaction assessment and seismic ground response modeling for Igbogene Town [6]. However, testing over a wider range of confining pressures would better characterize the pressure-dependent behavior, reflecting field stress variability with depth as indicated by Cubrinovski et al. [19].

Impact of a confining pressure of 100 kPa on Damping ratio:

The damping behavior of sandy soil subjected to a confining pressure of 100 kPa was investigated based on the energy dissipated per load cycle computed from hysteresis loops using Equation 1 recommended by Dobry et al. [8]. Figure 2 shows the variation of damping ratio (ξ) with increasing shear strain levels from 0.001% to 2% obtained from DSS testing.

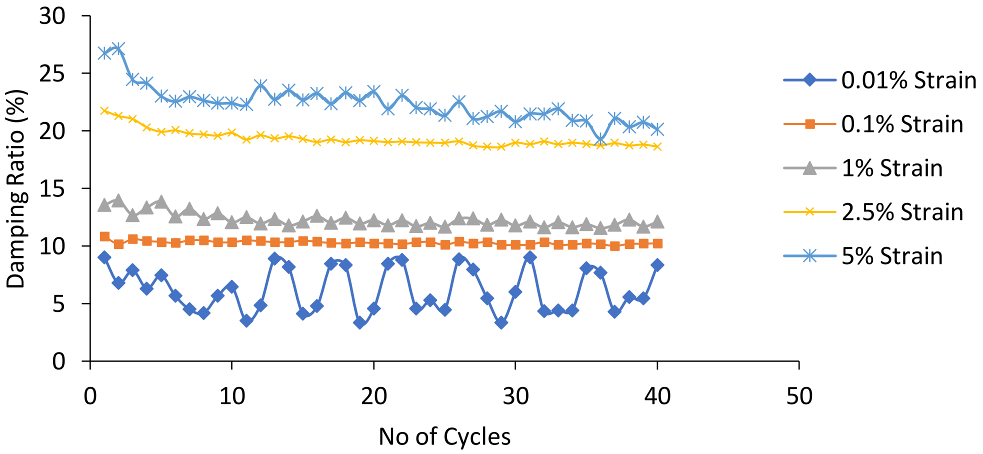

Fig. 2: Damping Ratio variation at 100kPa.

The damping ratio increased nonlinearly with shear strain as observed in previous studies. At small strains ($\gamma < 0.01\%$), ξ was minimal (<5%) but rose sharply beyond 0.01% strain. The trend is consistent with the trend reported for liquefiable soils by Santos et al. [16]. An empirical equation was derived by fitting the 100 kPa data to existing damping models discussed in Darendeli [18] to define the damping behavior for the sandy soil.The experimentally validated damping variation with strain and effective confining pressure provide crucial data for assessing seismic site response and liquefaction potential of sandy deposits in Igbogene Town. However, additional testing under higher confining stresses is suggested to develop a more comprehensive pressure-dependent damping characterization [19].

Impact of a Confining Pressure of 200 kPa on Shear Strain and Shear Modulus:

The effects of 200 kPa confining pressure on the dynamic properties of sandy soils from Igbogene Town, Niger Delta were investigated. Sandy soil samples that had not been disturbed and were taken from boreholes at effective confining pressures of 200 kPa were subjected to cyclic direct simple shear (DSS) testing by ASTM D6528 guidelines.

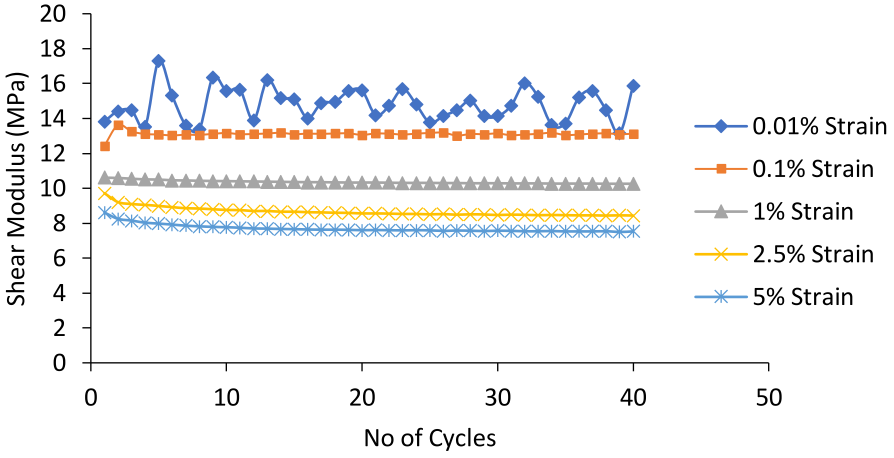

Fig. 3: Shear Modulus of Sandy Soil at 200kPa of Igbogene Town

Figure 3 shows the variation of normalized shear modulus (G/Gmax) with shear strain obtained from DSS tests. At very small strains ($\gamma < 0.001\%$), G remained relatively constant as reported in previous studies. With increasing strain, G reduced nonlinearly and followed an exponential decay trend consistent with the findings of Santos and Correia [16].The data was fitted to the empirical model proposed by Santos et al. [4] to quantify the shear modulus reduction behavior. A good correlation between the measured data and the model was observed, validating the model's applicability for soils in the study area under 200 kPa stress conditions. This confirms that confining pressure and shear strain influence shear modulus as emphasized by Dobry et al. [5].

Impact of a confining pressure of 200 kPa on Damping ratio :

The damping behavior of sandy soil under 200 kPa pressure was also investigated. Figure 4 depicts the variation of damping ratio (ξ) with shear strain obtained from DSS testing hysteresis loops using the energy method recommended by Dobry et al. [5].

The damping ratio increased nonlinearly with strain remaining minimal (<5%) at small strains but rising beyond 0.01% strain, consistent with trends for liquefiable soils reported by Santos et al. [16]. An empirical equation was fitted to existing damping models [18] to define the soil's damping behavior, validating the models.

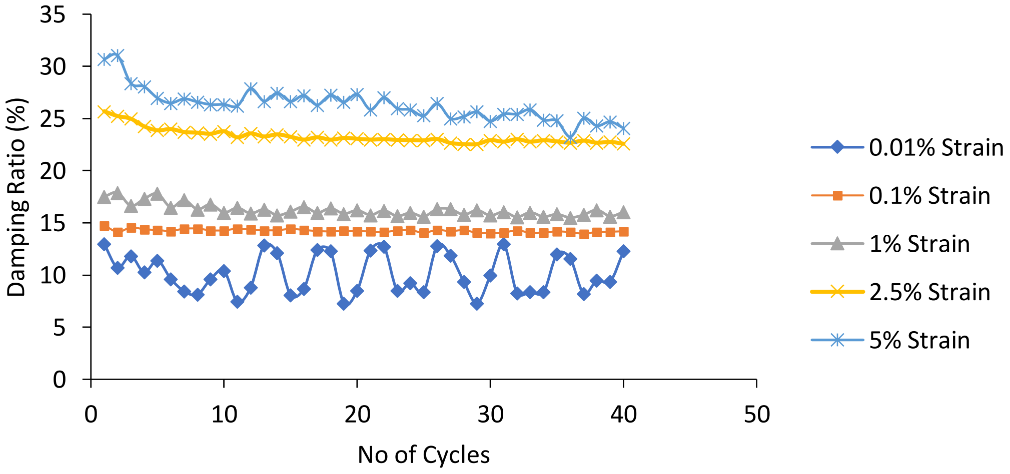

Fig. 4: Damping Ratio of Sandy Soil at 200kPa of Igbogene Town

The results provide input for seismic analyses as emphasized by Idriss and Boulanger [6]. However, testing over a wider range of pressures is suggested to better characterize pressure-dependent behavior reflecting variable field stresses with depth [19].

Impact of a Confining Pressure of 300 kPa on Shear Strain and Shear Modulus:

The impact of 300 kPa confining pressure on the dynamic properties of sandy soils from Igbogene Town was investigated. Cyclic DSS tests following ASTM D6528 were performed on undisturbed samples under 300 kPa effective stress.

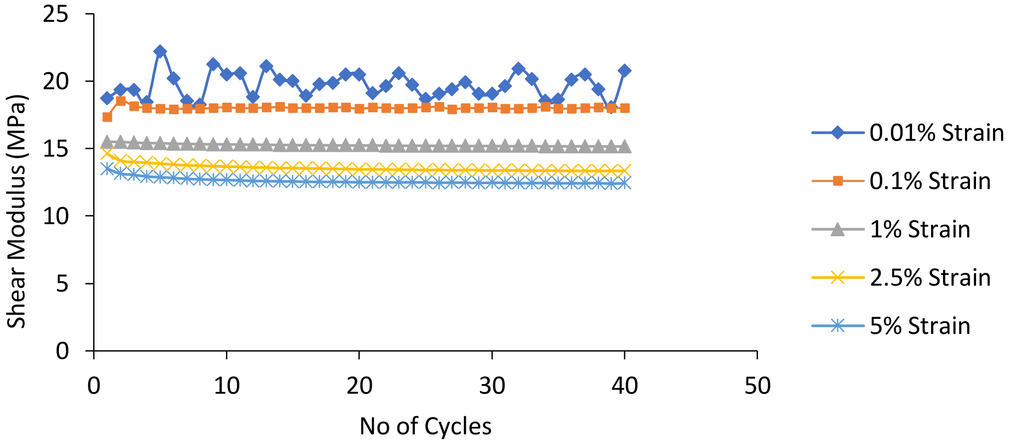

Fig. 5: Shear Modulus of Sandy Soil at 300kPa of Igbogene Town

Figure 5 shows the change in normalized shear modulus (G/Gmax) with shear strain. At very small strains ($\gamma <$ 0.001%), G remained relatively constant as reported previously. G reduced nonlinearly with increasing strain, consistent with an exponential decay trend observed by Santos and Correia [4]. The data was fitted to the empirical model by Santos et al. [4] to quantify shear modulus reduction behavior. A good correlation between measured and modeled data was observed, validating the model's applicability under 300 kPa stress conditions as suggested for site-specific soils.

Impact of a confining pressure of 300 kPa on Damping ratio:

Figure 6 presents the damping ratio variation with the shear strain curve obtained from DSS hysteresis loops using the energy method recommended by Dobry et al. [8]. ξ increased nonlinearly with strain remaining minimal (<5%) at small strains but rising beyond 0.01% strain, consistent with trends for liquefiable soils (Santos et al., 2012). An empirical equation fitted the 300 kPa data to existing damping models [18], corroborating these models.

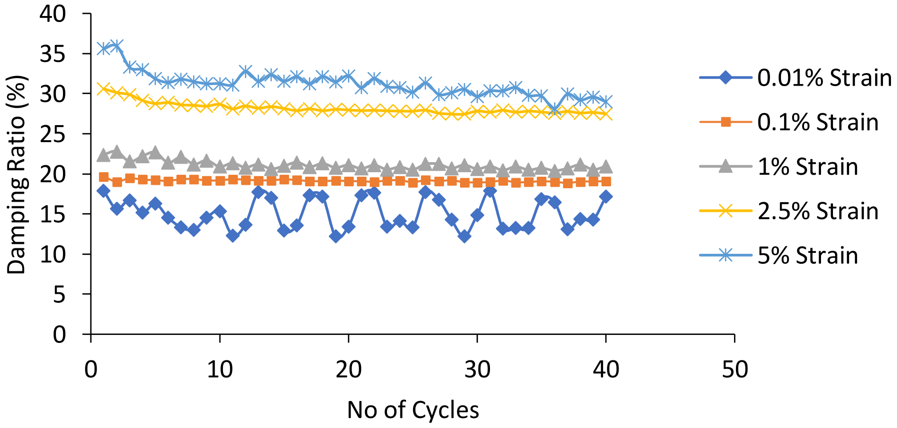

Fig. 6: Damping Ratio of Sandy Soil at 300kPa of Igbogene Town

The results aid seismic analyses as emphasized [6]. However, wider pressure testing would better characterize pressure-dependent behavior reflecting variable field stresses with depth [19]. The 300 kPa analyses validate empirical models and add to the understanding of dynamic soil behavior in Igbogene Town.

Impact of a Confining Pressure of 400 kPa on Shear Strain and Shear Modulus:

The impact of 400 kPa confining pressure on the dynamic properties of sandy soils from Igbogene Town was analyzed. Cyclic DSS tests compliant with ASTM D6528 were conducted on undisturbed samples under 400 kPa effective normal stress.

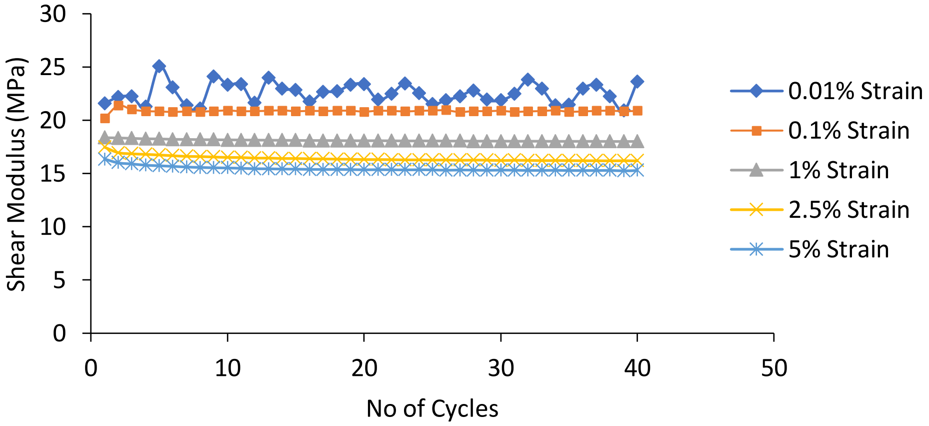

Fig. 7: Shear Modulus of Sandy Soil at 400kPa of Igbogene Town

Figure 7 depicts a variation of normalized shear modulus (G/Gmax) with shear strain. At very small strains ($\gamma < 0.001\%$), G remained relatively constant. G decreased nonlinearly with increasing strain, consistent with an exponential decay observed by Santos and Correia [16].

The data was fitted to the empirical model of Santos et al. [16] to quantify shear modulus reduction behavior. A good fit between measured and modeled data validated the model under 400 kPa stress, consistent with Dobry et al.'s [8] recommendation for site-specific soils.

Impact of a Confining Pressure of 400 kPa on Damping ratio:

Figure 8 shows damping ratio variation with strain from DSS loops using the energy approach of Dobry et al. [8]. ξ rose nonlinearly with strain, remaining minimal (<5%) at small strains but exceeding 0.01% strain, aligning with trends for liquefiable soils reported by Santos et al.[16]. The 400 kPa data correlated well to existing damping models [18], corroborating these relationships.

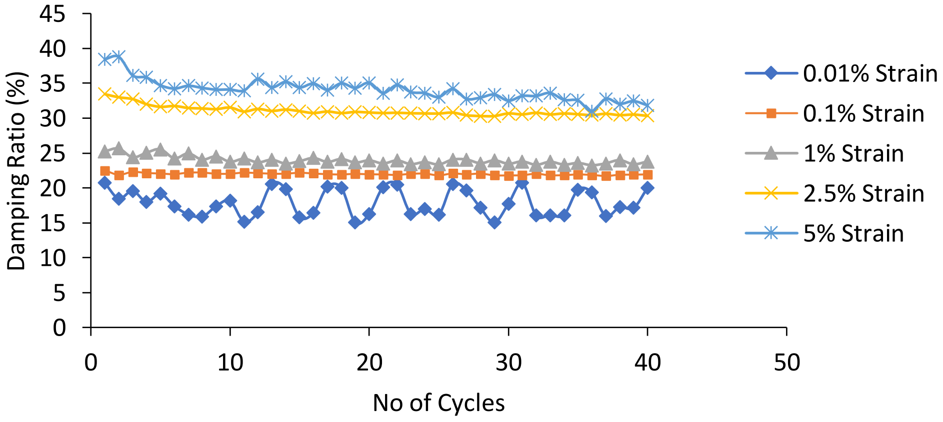

Fig. 8: Damping Ratio of Sandy Soil at 400kPa of Igbogene Town

The results inform seismic analyses as emphasized by Idriss and Boulanger [6]. Testing over a wider pressure range would better define pressure-dependent responses reflecting varying field stresses with depth. Analyses under 400 kPa stress extend understanding of Igbogene Town soil dynamics.

CONCLUSION

The study experimentally characterized the dynamic properties of sandy soils collected from Igbogene Town in the Niger Delta region of Nigeria under varying effective confining pressures up to 400 kPa. Cyclic direct simple shear tests were performed on undisturbed samples as per ASTM standards to investigate the influence of confining stress and shear strain levels on shear modulus and damping ratio.

The shear modulus was found to reduce nonlinearly with increasing shear strain, according by empirical exponential decay models proposed by Santos et al. (2012). The measured data correlated well with existing modulus reduction relationships, validating their suitability for the characterization of Niger Delta region soils at the studied confining stress levels of 100, 200, 300, and 400 kPa. This confirmed the crucial role of confining pressure and shear strain in controlling shear stiffness, in line with previous research findings.

The damping ratio exhibited an upward nonlinear trend with shear strain, remaining below 5% at small strains but rising beyond 0.01% strain levels. The damping behavior followed patterns documented for liquefiable soils. Empirical equations fitted the experimental data and corroborated existing damping models by Darendeli (2001).

The research provided valuable input for developing shear modulus degradation and damping variation curves needed in seismic site response and liquefaction evaluations of sandy sequences in the Igbogene Town area. However, additional testing under a wider confining stress range would better define the pressure dependency of dynamic properties reflecting varying in-situ stresses with depth.

Overall, the study successfully characterized the small to medium shear strain behavior of sandy soils from the Niger Delta through cyclic lab testing. The experimentally validated empirical models enhance understanding of dynamic soil response in the region and aid geotechnical seismic hazard assessments. Further research incorporating larger samples and a wider range of parameters would build upon these findings.

Credit authorship contribution statement

GMSA: Conceptualization, Methodology, Funding Acquisitions, Writing–original draft, Writing–review and editing.

CK: Conceptualization, Investigation, Data curation, Methodology, Writing–original draft.

GM: Formal Analysis, Writing–original draft, Writing–review and editing.

MAS: Formal Analysis; Data curation, Writing–review and editing.

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