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Dynamic properties of silty sand

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ABSTRACT

Investigating dynamic soil properties is essential for understanding soil characteristics and their behavior under various dynamic or cyclic loading conditions, such as those induced by seismic events or construction activities. This understanding is vital for the geotechnical engineering industry to design foundations and structures capable of withstanding seismic forces. This study employs the resonant column apparatus (RCA), renowned for evaluating soil behavior at small-strain levels.
The study examines the dynamic soil properties of the capital city of Kazakhstan, Astana. Even though Astana is not prone to significant seismic activity, the city's residents recently felt aftershocks from earthquakes in China and Kyrgyzstan, 1600-3000 km away from Astana. Understanding every city's dynamic soil properties is crucial for assessing seismic hazards and disaster prevention.
Resonant column (RC) and cyclic torsional shear (CTS) tests were conducted to derive site-specific shear modulus reduction curves and material damping ratio (D) curves for small-to-intermediate shear strain values under varying experimental conditions of confining pressure (σ_c). This research seeks to fill the knowledge gap regarding the dynamic properties of silty sand soils and aims to enhance regional seismic risk mitigation strategies, especially in areas susceptible to earthquakes.

1. INTRODUCTION

Understanding soil behavior under various loading conditions, such as during earthquakes or construction operations, is crucial for maintaining the safety and stability of foundations and other structures. Earthquakes can cause soil liquefaction, a phenomena that weakens the soil and jeopardizes the strength of systems, resulting in road distortions, construction tilting, and bridge failures (Moon et al. 2024). This necessitates a thorough understanding of dynamic soil properties, which are essential in architectural and geotechnical fields, including foundation design, and probabilistic seismic hazard assessment (PSHA).

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Various laboratory and field-testing methods are employed to investigate these dynamic soil properties. Field-testing methods include seismic refraction, reflection, and multi-channel analysis of surface waves (MASW) (Abdialim et al. 2024), while laboratory testings contain resonant column, bender element, cyclic triaxial and torsional tests. The information obtained from these tests is used to develop strategies for mitigating the impact of dynamic stresses on structures, establish seismic design guidelines, and assess soil-structure interactions.

The resonant column apparatus (RCA) test methodology is particularly effective for assessing the dynamic properties of soil within a relatively small strain range. In the RCA test, a cylindrical soil sample is vibrated in either torsional or flexural modes. This method effectively determines critical characteristics of soft rocks and soils, such as shear modulus (G), material damping (D), and shear strain (Sas et al. 2017). The primary objective is to understand the variables influencing soil stiffness by analyzing dynamic properties under various confining pressures (σ_c) and strain amplitudes.

To date, there has been limited investigation into the dynamic soil properties of Kazakhstan using the RCA test. Approximately 25% of Kazakhstan's territory, particularly in the South, Southeast, and East, is vulnerable to earthquakes due to its geological situation (Zhanabayeva et al., 2023). Although seismic activity is relatively low in Astana, residents have felt aftershocks from distant earthquakes in China and Kyrgyzstan. Residential buildings constructed before the 1990s lack seismic resilience, increasing susceptibility even when built with various materials and seismic-resistant techniques (Rashid et al. 2023).

Over the past 50 years, Kazakhstan's seismic design regulation framework has updated, originally drawing from Soviet research. Since their publication in 1998, the first extensive building norms, or SNiP, have undergone revisions to include new developments in seismic engineering and global research (Zhanabayeva et al. 2023). Comprehensive site characterization is critical, especially in the regions prone to earthquake. Therefore, this study aims to address a significant knowledge gap by employing advanced soil testing methods and the Resonant Column device to precisely investigate the dynamic properties of silty sand. The primary objective is to evaluate these properties, enabling the development of material damping ratio (D) curves and modulus reduction curves, thereby enhancing the region preparedness for seismic events. Achieving this research objective will significantly contribute to seismic risk reduction and geotechnical construction, ultimately leading to safer infrastructure.

2. EXPERIMENTAL WORKS

2.1 Materials

The materials were sourced from an active construction site in Astana, Kazakhstan. The near-surface soil layer was identified as silty sand, with a moisture content (MC) of 14.0% and a maximum dry density (MDD) of 1.868 Mg/m^3, as shown in Fig. 1. The specimen preparation and testing processes adhered to the ASTM D4015-2014. Samples were prepared using conventional dimensions of 140 mm in height and 70 mm in diameter. The MDD and MC were maintained throughout this procedure to accurately replicate field conditions.

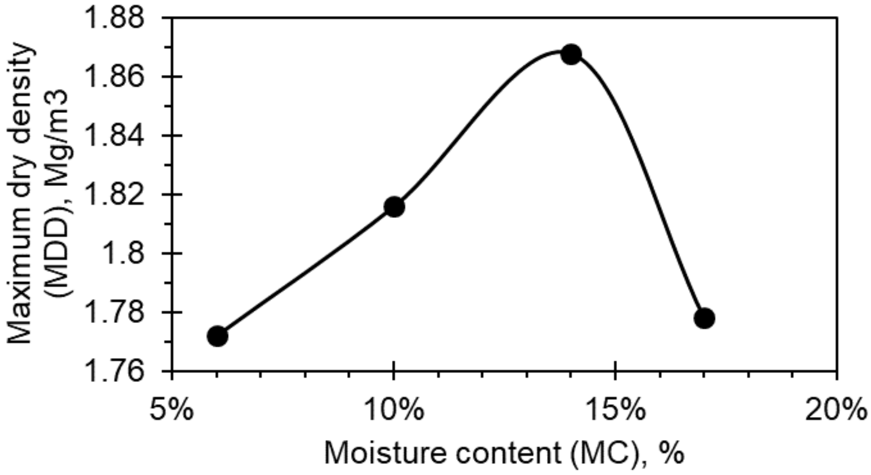

Fig. 1 MC and MDD of silty sand

2.2 Resonant Column Apparatus (RCA)

The RCA is a highly effective tool for assessing dynamic soil properties, capable of performing both resonant and cyclic torsional shear tests (Rohilla and Sebastian 2023). This experiment utilized the GDS instruments' Resonant Column setup, as shown in Fig. 2. This device is particularly useful for examining the dynamic characteristics of samples under low-to-intermediate strain levels. The RCA employs an electromagnetic system to apply a small cyclic torsional force to a prepared soil sample. The shear modulus (G) is determined by measuring the sample's response with a drive system and sensors (such as accelerometers and linear variable differential transformers [LVDTs]) and adjusting the load frequency to achieve resonance (Szilvágyi 2018). This method effectively investigates the effects of low strain levels (ranging from 10^{-5} to 10^{-1} percent) with various confining pressures. The apparatus was configured to stimulate torsional vibration within a voltage amplitude of 0.001 to 1 V to achieve the minimum and maximum strain values.

Fig. 2 Resonant Column Apparatus (RCA): (a) RCA device, (b) system hardware, (c) back pressure

2.3 Testing procedure

GDSLab and GDSRCA software programs were used for data acquisition. The specimen was saturated and consolidated using the following procedures before beginning the resonant column (RC), damping, and cyclic torsional shear (CTS) tests:

The apparatus was first cleaned, and de-aired water was added to the pore pressure system to eliminate air gaps, ensuring no bubbles were present. Filter papers were placed on the top and bottom surfaces of the specimen to expedite the consolidation phase and facilitate water distribution throughout the pore pressure system. The specimen, once fitted into the cell, was enclosed with two latex membranes to minimize air transmission. The back pressure method was employed to saturate the silty sand.

After dissolving the air in the intergranular spaces with a small amount of cell and back pressure, the test sample was properly saturated by gradually increasing the cell and back pressure until Skempton's B-value exceeded 0.95 (Sas et al. 2017). The consolidation procedure was then initiated at a confining pressure (σ_c) of 50 kPa. This process continued until the initial phase was complete, typically taking one to two days, but occasionally extending up to 48 hours (Flores-Guzmán et al. 2014). Subsequently, data collection for the RC, damping, and CTS tests began. These procedures were repeated for confining pressures of 100 and 150 kPa.

The saturation phase ensures that the soil specimens are in a truly saturated state, mimicking field conditions (B-value > 0.95), while the consolidation stage provides insights into soil behavior under applied loads, particularly long-term settlement behavior. These phases are essential for accurate geophysical analysis, foundation design, and the prediction of soil and stone material properties in various construction and engineering projects.

3. RESULTS AND DISCUSSION

3.1 Shear Modulus vs. Shear strain

Fig. 3 illustrates the variation of shear strain with the shear modulus (G) for both resonant column (RC) and cyclic torsional shear (CTS) tests at confining pressures (σ_c) of 50, 100, and 150 kPa. The trends in

Fig. 3 clearly indicate that the shear modulus increases with an increase in σ_c, suggesting that greater depths are associated with higher dynamic G values. This increase in shear modulus is attributed to the denser grain packing resulting from higher σ_c, which enhances material stiffness and subsequently raises the shear modulus (Adari et al. 2023). Additionally, the higher density of the material contributes to a higher dynamic G, as stronger interparticle interactions associated with greater material densities result in elevated shear moduli. At low strains, a linear response is observed, with a constant shear modulus (G) up to a strain threshold of approximately 0.03%. Beyond this threshold, nonlinear behavior is anticipated, likely due to particle rearrangement and potential failure mechanisms.

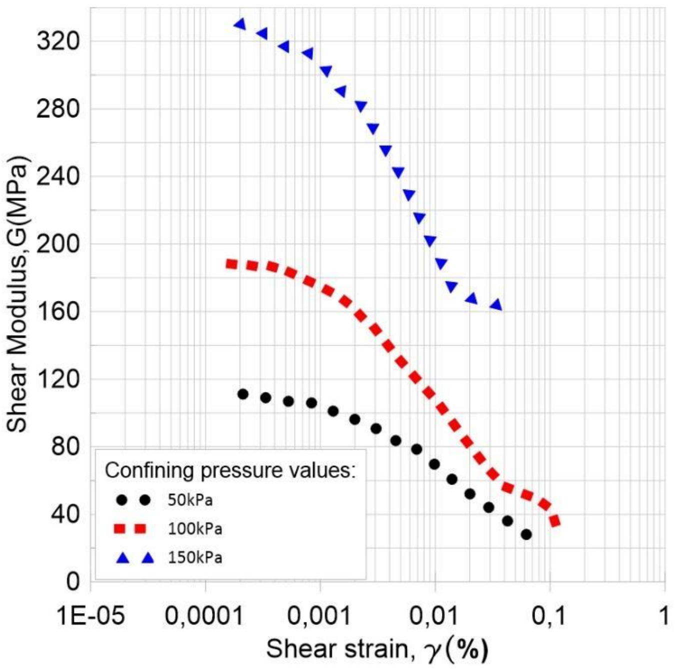

Fig. 3 Shear Modulus vs. Shear strain for different σ_c

3.2 Damping ratio vs. Shear strain

Fig. 4 depicts the fluctuation of the damping ratio (D) with shear strain for both tests at confining pressures of 50, 100, and 150 kPa. It is evident that, in accordance with the hysteretic loop hypothesis, D values increase as shear strain increases (Adari et al. 2023). According to this hypothesis, larger cyclic loading amplitudes result in higher D values due to increased energy loss. Furthermore, the damping ratio of the soil does not significantly vary with changes in σ_c, as the fundamental material properties remain unchanged across the examined range.

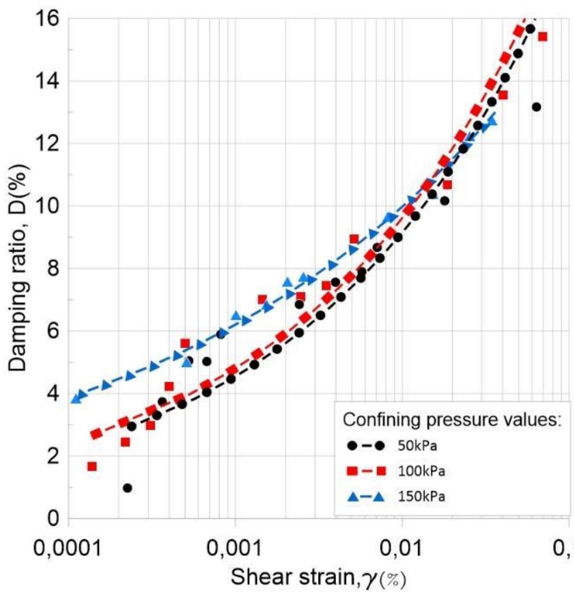

Fig. 4 Damping ratio vs. Shear strain for different σ_c

4 CONCLUSION

This study employed advanced soil testing methods using the Resonant Column Apparatus (RCA) to provide detailed insights into the dynamic soil properties of Astana, Kazakhstan. The cyclic response of soil was examined under different confining pressures (σ_c) of 50 kPa, 100 kPa, and 150 kPa in the small-to-intermediate strain range of 10^{-5}% to 10^{-1}%. The findings of this experiment led to the following conclusions:

1. The analysis of shear modulus (G) versus shear strain indicated that the shear modulus increases with an increase in σ_c. This suggests that denser grain compaction in deeper soil layers results in larger dynamic shear moduli. Additionally, consistent shear modulus values and linear rates were observed at low strains up to a threshold of 0.03%, with nonlinear behavior anticipated at higher shear stresses due to potential failure mechanisms and particle rearrangement.
2. According to the hysteric loop concept, D values increase with increasing shear strain, as demonstrated by the analysis of D variations with shear strain. Despite variations in shear strain, the D of silty sand showed minimal response to changes in σ_c, indicating consistent sample quality over the examined range.

Overall, the study's conclusions enhance our understanding of Astana's dynamic soil properties, contributing to improved infrastructure development and seismic hazard assessment in the city. Further research and analysis are required to build upon these findings and enhance preparedness for seismic events and urban resilience in high-risk areas.

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