Particle Crushing and Liquefaction Resistance of Crushable Aragonite Sands

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ABSTRACT

The influence of soil crushability on the strength parameters of aragonite sand under cyclic undrained conditions is investigated in this study. The investigation used aragonite sand, which is known for being susceptible to crushing under normal loading conditions. A series of cyclic simple shear tests were carried out at different normal loads of 100kPa, 150kPa, 200kPa, and 250kPa under a constant confining pressure. To maintain consistency in particle crushing, sieving tests were used to assess the level of particle breaking, with testing stopping after a predetermined number of cycles. The results show that particle crushing increased the fines content of the soil, even when the effective stress was low during the undrained shear phase. The liquefaction resistance of aragonite sands increased as normal load increased. These findings show the major influence of soil crushability on the engineering behavior of aragonite sand, implying that conventional assumptions about the link between normal load and liquefaction resistance may not be true for crushable soils.

Keywords: Particle breakage, Liquefaction, Cyclic Simple Shear.

1. Introduction

Particle breakage and its significant influence on soil behavior have been the focus of numerous research endeavors conducted in recent years (e.g., Hardin 1985; Mao and Fahey 2003; Porcino et al. 2008; Yu 2018). The process of particle breakage induces alterations in soil gradation, subsequently influencing the overall soil response; for instance, it disrupts the dilatancy of granular soil, leading to increased contractive behavior. This effect becomes evident when observing the movement of the critical state line on the e-logp plane – the plane involving void ratio (e) and the logarithm of mean effective stress (p) – which shifts downward with increasing levels of particle breakage. Therefore, to get insight into the changes in soil properties caused by particle breakage, it is critical to quantify the changes in particle distribution and size caused by loading in laboratory experiments. Many researchers have quantified and reported the response of crushable granular materials using isotropic consolidation tests, monotonically triaxial compression and extension tests. A few studies have also utilized cyclic triaxial tests to explore the effect of particle breakage. In the study by Asadi et al. (2018), it was observed that dense natural pumiceous materials, which are inherently prone to crushing, exhibited an approximately twofold increase in relative breakage compared to loose natural pumiceous materials under undrained cyclic triaxial conditions. Additionally, the research revealed that natural pumiceous materials exhibited greater resistance to liquefaction than Hard grained Toyoura sand. A similar pattern concerning the extent of particle breakage has also been reported by Hyodo et al. (2017) on Aio sand under same test conditions. Liu et al. (2015) conducted a series of monotonic triaxial experiments and determined that pumice sands, regardless of relative density, exhibited an unchanged stress path under specific confining pressures. Nonetheless, there exist only a limited number of studies that take into account the influence of particle breakage through the utilization of cyclic simple shear instruments, which offer greater versatility and accuracy when compared to the aforementioned approaches. A large number of studies have been conducted on particle breakage and its influence on soil behaviour under various loading conditions. Monotonic and cyclic triaxial tests are commonly employed(e.g. Asadi et al. 2018; Cao et al. 2021; Donohue et al. 2009; Hyodo et al. 2017; Salem et al. 2013; Wang and Zha 2020; Yu 2017a; b, 2018, 2017c), however many geotechnical problems in the field mimic simple shear conditions, and few studies have reported on the behaviour of carbonate sands under cyclic simple shear (Ji et al., 2018; Mao & Fahey, 2003; Porcino et al., 2008). This underscores the need for additional investigation in this research field.

Cyclic simple shear tests allow for more realistic simulation of shear behavior during earthquake loading. The simple shear condition is closer to the actual deformation mode experienced by soil deposits during seismic events. The cyclic simple shear apparatus enables a smooth and continuous 90-degree rotation of the principal stress direction, replicating the situation of principal stress rotation. In contrast, in cyclic triaxial tests, the major principal stress always aligns either parallel or perpendicular to the vertical axis., whereas in cyclic triaxial tests, the major principal stress is always parallel or perpendicular to the vertical axis.

The current study considers a aragonite sand (known to crush) and investigates the degradation of this material during undrained cyclic simple shear loading by

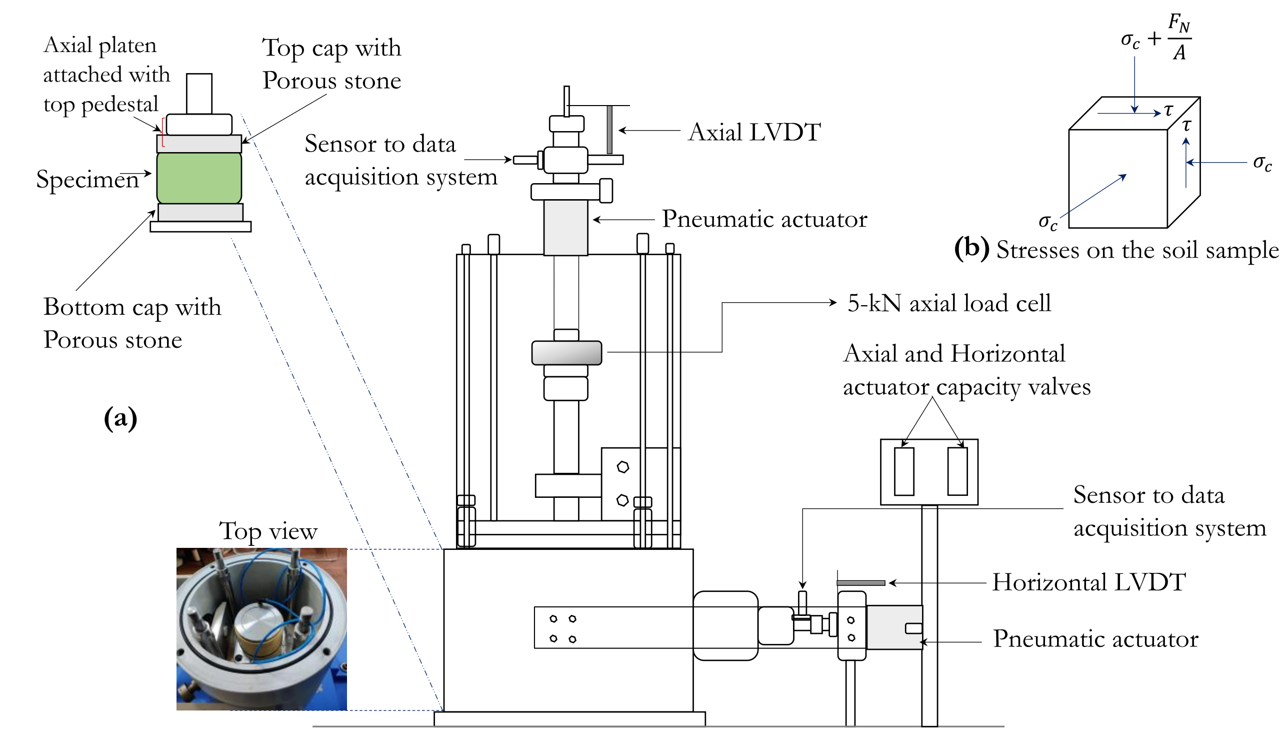

Figure 1. (a) Schematic representation of the CSS instrument; (b) Force body diagram of the specimen.

quantifying particle breakage. The main reason for selecting aragonite sand for study soil is that it is vesicular in nature and consists primarily of the remains of marine organisms, making it extremely susceptible to crushing under normal engineering stress levels, and the soil properties of coral sand such as mineralogy, maximum and minimum void ratios, and specific gravity are found to be within the range of calcareous sands as reported in literature. To understand the effect of particle breakage on the undrained behaviour of coral sand, a series of cyclic tests with a relative density equal to 60% under a broad range of normal loads were conducted. The number of cycles required to cause liquefaction (pore water pressure ratio r_u reaches 1or a specified axial strain amplitude (ε=5% in double amplitude) is usually defined as the failure criterion. The effect of particle crushing on pore-water pressure generation is investigated.

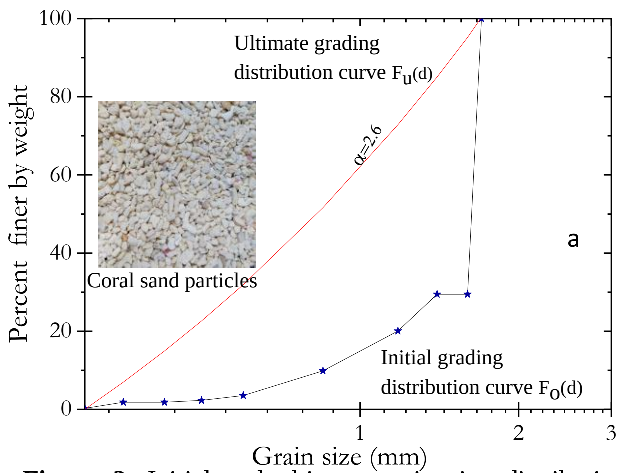

Figure 2. Initial and ultimate grain size distribution (GSD) curves of coral sand.

2. Materials and Experimental Methods

This study used a commercially available carbonate sand (aragonite sand) that primarily contained aragonite minerals, which are highly susceptible to crushing even under typical loading conditions due to their vesicular structure. According to the Unified Soil Classification System, the soil is categorized as poorly graded sand (ASTM D2488). Fig. 2 shows the tested sand's grain size distribution curve**.** The C^2 method ASTM (D4254-00), ASTM (D4253-00), and IS2720 (Part 3-1980) were used to measure the index properties of the materials, and the results are summarised in Table 1. Scanning electron micrographs of similar material, as shown by Das et al. (2019), clearly demonstrate the presence of a considerable quantity of intra particle voids, which makes the sand susceptible to crushing under a moderate stress.

Table 1. Physical properties of coral sand

Property	
Specific gravity, G_s	2.70
Minimum void ratio, e_{min}	1.003
Minimum void ratio, e_{max}	1.263
Coefficient of uniformity, C_u	1.875
Coefficient of curvature, C_c	1.408

A cyclic simple shear (CSS) testing apparatus was used to do the experiments. Fig. 1 depicts a schematic illustration of the apparatus with a top view of a half cell with the force body diagram acting on the soil sample. The equipment features a pneumatically controlled base system with a maximum cell pressure of 1MPa, a dual-axis 5-kN load cell that controls and measures axial and lateral loads, and a wide range of cyclic loading frequencies ranging from 0.001 to 5 Hz. An extremely precise feedback mechanism regulates the applied force and the resulting displacement. The axial platen is attached to the top-cap of the specimen and can be moved only axially, while the horizontal platen is attached to the pedestal at the base of the specimen and can be moved along the horizontal axis. The density and stiffness of the soil specimen undergo changes with the number of cycles under cyclic loading. All simple shear test specimens were formed by the moist tamping method to provide uniformity and prevent segregation. The simple shear specimen's target sizes were 100 mm in diameter and 30 mm in height. The sample was placed in a latex membrane that was secured to the bottom pedestal with O-rings. The soil particles were first submerged with water prior to sample preparation to form moist soil samples. In order to achieve a target relative density after consolidation corresponding to Dr 60%, the specimen was prepared in a sample split mould on top of the base of the simple shear apparatus. Each specimen was prepared in three layers in the sample split mould using a procedure similar to the under-compaction method proposed by Ladd (1978) to ensure uniform density throughout the specimen (Amini & Qi, 2000). For each specified density, a pre-weighed amount was used for each layer, which was then compressed down with a tamper to a predetermined height to achieve the target required density. When the target specimen height was reached, the top cap was placed on top, along with a filter paper of the soil sample. Before removing the split mould, a small amount of suction pressure (10-15 kPa) was applied from the base of the sample to make it stand on its own without any disturbance. The simple shear cell was assembled and then filled with water. The next step was to fully saturate the sample by slowly increasing the cell and back pressures over 24 hours. A back pressure of 300 kPa was used to achieve a Skempton B-value at least 0.95. After making sure the sample was fully saturated, the cell pressure was raised to consolidate the sample isotropically under a certain effective confining pressure. Since the sample consolidated in an isotropic way instead of using a set of stacked rings stacked on top of each other, as many researchers do to study anisotropic consolidation (Al Tarhouni & Hawlader, 2021). One problem with using stacked rings is that radial stress cannot be measured during shearing. Because of this, a Mohr Circle must be made based on assumptions. So, isotropic consolidation may be the easiest way to get rid of all of these assumptions. The simple shear tests were conducted in the constant volume condition, which corresponds to the undrained condition also known as the constant volume test. A control system keeps total vertical stress constant during the shearing phase. This is accomplished by unlocking the vertical loading ram and varying the cell pressure with the control system to maintain a constant total vertical stress. The specimen was compressed to a specific normal load under drained conditions prior to shearing.

There are two definitions of liquefaction: (1) When the excess pore water pressure ratio $r_u = (p_i - p_c)/p_i$ approaches 1. r_u is defined as the ratio of the difference between the initial mean and current mean effective stresses over the initial mean effective stress. The mean effective stress is almost zero at this point, and (2) when a specified shear strain amplitude of $\varepsilon_a = 5\%$ in double amplitude is reached. This stage, known as soil, is in a liquefaction state. The undrained cyclic tests were specifically terminated after 100 cycles to ensure consistency of particle breakage caused by cyclic loading Understanding effect of normal load on the behavior of coral sand under cyclic simple shear loading is paramount for several pivotal reasons relevant to geotechnical applications specially for offshore regions. Normal load affects the mechanical interactions between sand grains, including contact forces and potential grain breakage, thereby altering the stiffness and its deformation response under cyclic loads. Moreover, normal load plays a crucial role in the evolution of pore water pressure within the coral sand matrix during cyclic loading. Higher normal loads increase the matrix density and confinement, which can accelerate the buildup of pore water pressure, a critical factor in the onset of liquefaction where the sand loses its strength and stiffness. Additionally, the coral sand initial packing density, significantly affected by the applied normal load, determines its susceptibility to deformation and failure under cyclic loading. Thus, understanding the effect of normal load is essential for predicting the behavior of coral sand in applications subject to cyclic loading, such as earthquake engineering and offshore foundation design. In the study, the effect of normal load is investigated via the pore water generation and associated particle breakage of coral sand under cyclic simple shear.

3. Undrained cyclic simple shear response

To explore the behavior of coral sand under cyclic simple shear, specimens were initially isotropically consolidated, then subjected to a specific normal load under drained conditions. Subsequently, shear loading was applied at an amplitude of ±1.5mm and a frequency of 0.2Hz under undrained conditions, with a relative density of 60% (initial void ratio e0 = 1.107). The study aimed to evaluate the impact of varying normal loads (ranging from 100 to 250 kPa) on particle breakage and the evolution of pore water pressure. All tests were conducted under strain-controlled conditions, with a uniform confining pressure of 300 kPa.

3.1. Effect of Normal Load

Stress path and stress strain plot at a normal load 100 kPa under the confining pressure shown are illustrated in Fig. 3. The rate of generation of excess pore water pressure decreased with increasing normal load on the cyclic simple shear specimen under constant confining pressure, reaching a threshold value. For example, at 100kPa normal load, the EPWP threshold value is 0.80, whereas at 250kPa normal load, the EPWP threshold value is 0.64. According to Fig. 4, coral sand exhibits higher liquefaction resistance at higher normal load when prepared and tested under similar relative densities and effective confining pressure. The findings are consistent with those reported in the literature (Park et al., 2020). Hubler et al. (2018), on the other hand, revealed that initial vertical stress has no effect on the number of cycles to liquefaction in experiments on gravelly soils using cyclic simple shear.

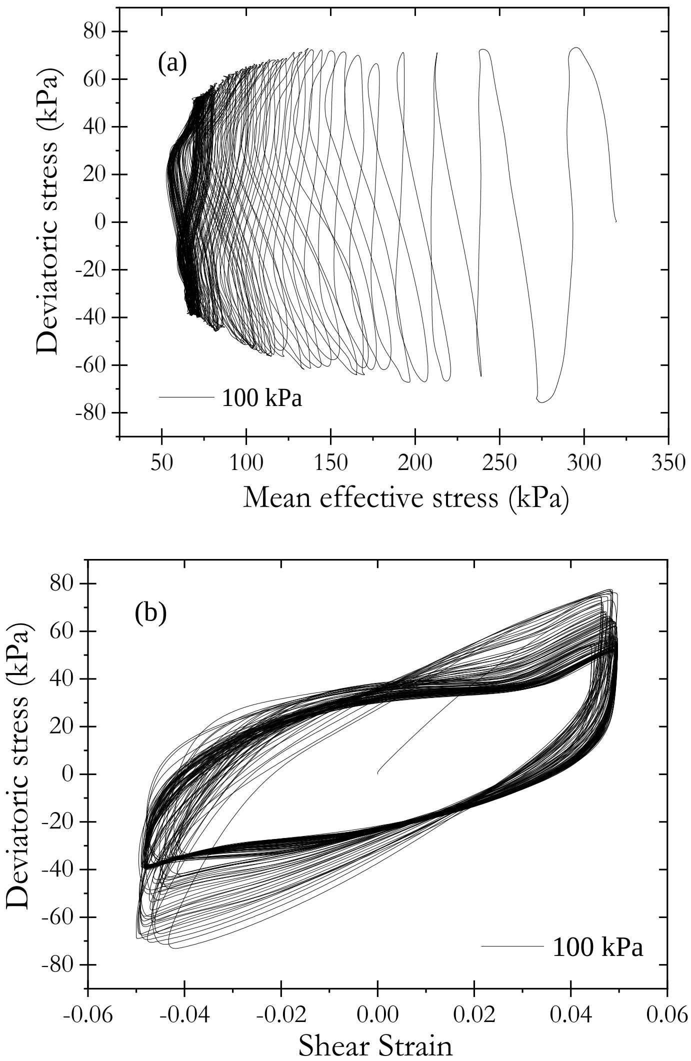

Figure 3. Undrained cyclic simple shear response of coral sand: (a) stress path; (b) stress-strain curve at e_0=1.03 and 100 kPa normal load.

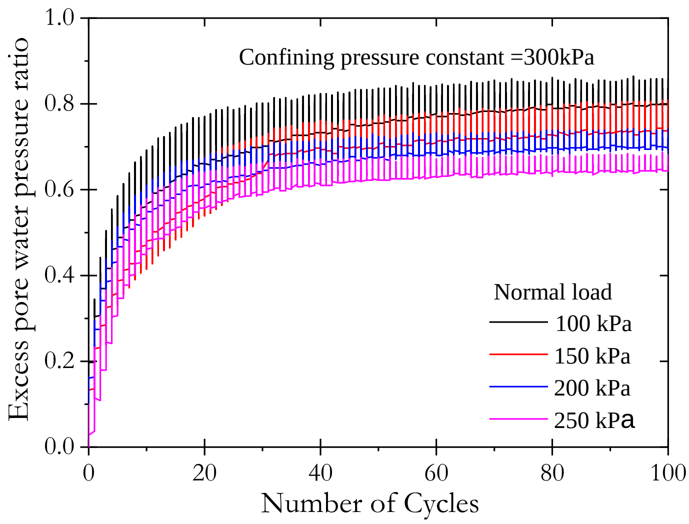

Figure 4. Evolution of excess pore water pressure ratio with number of cycles at medium-dense at e_0=1.03 under different normal loads.

4. Particle Breakage Analysis

It is critical to propose an index capable of accurately quantifying particle breakage during loading. In this study, a modified Hardin's breakage index B_r proposed by Einav (2007) is used to quantify the degree of grain crushing. The schematic representation of modified relative breakage (B_r) is shown in Fig. 5. B_t denotes total breakage and is the area between the initial ($F_0(d)$) and current ($F(d)$) cumulative grain-size distribution curves, which are represented in cyan. B_p is the area between the initial ($F_0(d)$) and final $F_u(d)$ cumulative grain-size distribution curves, which represents the breakage potential represented by the sparse pattern. The degree of breakage is represented by the B_r value, which can range from 0 to 1.

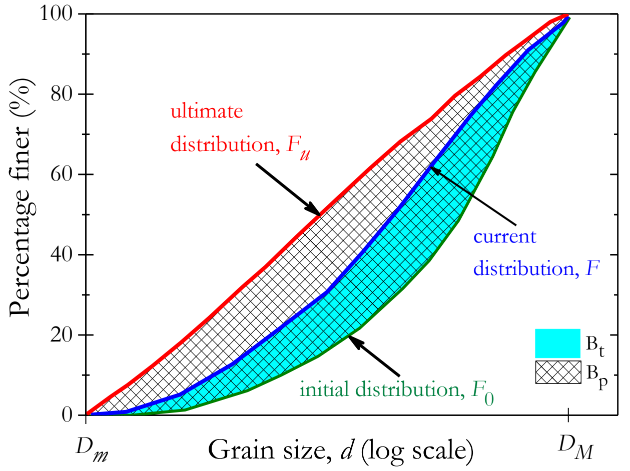

Figure 5. Definition of breakage index, B_r, by (Einav, 2007b)

Superstructure load during earthquake shaking is critical for soil liquefaction potential. Normal load in a cyclic simple shear instrument simulates the same in the laboratory, and there is no study in the literature on the effect of normal load on particle breakage quantification. It is evident that with an increasing normal load, particle breakage decreases, resulting in a higher evolution of pore water pressure ratio with the number of cycles, as shown in Fig. 6. As shown in Fig. 4, the rate of generation of excess pore water pressure is faster at low normal load than at high normal load under constant confining pressure. The possibility of high pore water pressure ratio at more breakage due low normal load is attributed to crushed particles moving to voids, resulting in fewer contact points among particles and, eventually, contraction. Thevanayagam et al. (2002) reported that if the fines content (analogous to particle breakage) is greater than a certain threshold fines content, then fine grain contact plays an important role on overall soil matrix.

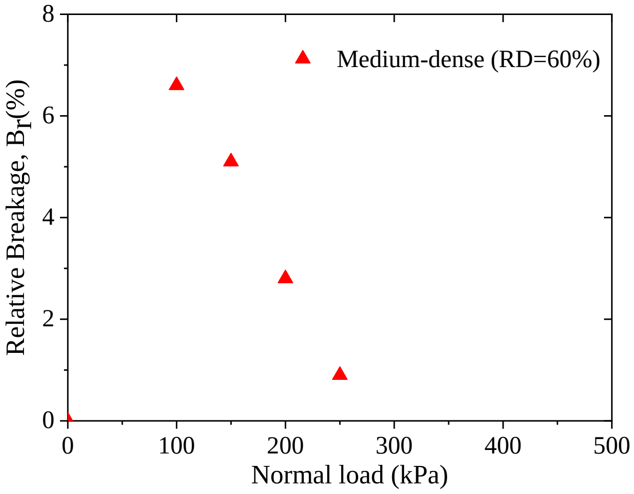

Figure 6. Relative breakage plotted against Normal load.

5. Conclusions

A series of cyclic simple shear tests were conducted on medium dense samples of coral sands to evaluate how particle breakage affects liquefaction resistance. The primary findings from these tests can be summarized as follows. 1) The rate of excess pore water pressure generation decreased as the normal load on the cyclic simple shear specimen increased while maintaining a constant confining pressure. 2) When coral sand samples were prepared and tested at similar relative densities and effective confining pressures, higher normal loads resulted in increased liquefaction resistance. 3) Increasing the normal load led to a reduction in particle breakage, consequently causing a greater evolution of pore water pressure ratio with the number of cycles.

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