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Centrifuge Study on Carbonation Effects in Calcareous Sand

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ABSTRACT: The long-term geochemical evolution of reclaimed calcareous sand deposits and its influence on soil behaviour remain insufficiently understood, particularly the effects of calcium carbonate ($CaCO_3$) dissolution. This study investigates the impact of carbonation on reclaimed calcareous sand by inducing controlled chemical alteration at 1 g and subsequently evaluating mechanical response using 40 g centrifuge zone load tests. Carbonation was achieved through sustained injection of carbon dioxide (CO_2) enriched pore water, resulting in a progressive reduction in pore-water pH. Continuous pH monitoring confirmed effective and depth-dependent carbonation within the soil profile. Comparisons with an identical non-carbonated deposit show a reduction in stress mobilisation after carbonation. The results show that carbonation-induced dissolution processes representative of reclaimed island can be effectively reproduced in the laboratory.

1 INTRODUCTION

In the context of climate change, rising atmospheric carbon-dioxide (CO_2) concentrations and sea-level rise are expected to increasingly alter the geochemical environment of coastal and offshore soils. Many reclaimed islands in arid and subtropical regions are constructed using calcareous sands, whose long-term performance under evolving environmental conditions remains uncertain.

Calcareous sands differ fundamentally from quartzitic sands, as they consist primarily of biogenic calcium carbonate ($CaCO_3$) fragments derived from corals, shells, and skeletal remains. When exposed to CO_2-rich pore water in marine or engineered environments, these soils undergo carbonation-induced dissolution, leading to partial $CaCO_3$ degradation (Opukumo, Glendinning, and Davie 2024). Such mineralogical alterations can modify interparticle contacts, surface roughness, and local stiffness, thereby influencing the mechanical and dynamic behaviour of the soil matrix (Giretti et al. 2025). Despite their widespread application in coastal engineering, the coupled chemical–mechanical response of calcareous sands subjected to carbonation remains inadequately understood.

Replicating long-term carbonation processes within geotechnical centrifuge modelling poses significant experimental challenges. To address this gap, the present study induces controlled carbonation at 1 g and subsequently investigates its effects on soil behaviour using centrifuge-based zone load testing, with particular emphasis on bearing response.

2 EXPERIMENTAL PROGRAMME

Two model tests were conducted at 40 g in the New York University Abu Dhabi centrifuge facility. The physical model was constructed inside a rigid rectangular box with internal dimensions of 1050 mm length, 360 mm width, and 175 mm height, representing a horizontally layered reclaimed calcareous sand deposit. The setup was designed to investigate the effect of carbonation on reclaimed islands. A reclaimed calcareous sand layer (7 m prototype thickness) was saturated with seawater. One model was carbonated for 37 days using CO_2-enriched water; the other without carbonation served as a reference. Tests included zone load tests at 40g for case without and after carbonation.

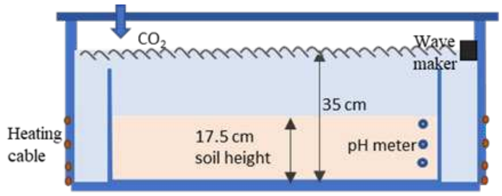

Figure 1 Arrangement of soil model for carbonation

Figure 1 shows the arrangement of the soil model and the carbonation setup. CO_2 was introduced from the top boundary to dissolve into the overlying fluid and diffuse into the soil mass. A wave maker was used to generate mild surface agitation, simulating wave-induced mixing in marine environments and enhancing CO_2 dissolution at the fluid–soil interface. Heating cables installed along the container sidewalls were used to elevate and regulate temperature, representing increased environmental temperatures and accelerating carbonation reactions. pH meters were installed at multiple depths to continuously monitor the spatial and temporal evolution of pore-water chemistry during carbonation.

3 RESULTS AND DISCUSSIONS

Carbonation in calcareous sands results from the interaction between CO_2-enriched pore water and $CaCO_3$ particles, where dissolved CO_2 forms carbonic acid that partially dissolves $CaCO_3$. This process alters pore-water chemistry, reduces alkalinity, and progressively modifies particle surfaces, interparticle contacts, and the buffering capacity of the soil, with implications for subsequent mechanical behaviour. In this study, carbonation was carried out at 1 g by exposing a fully saturated reclaimed calcareous sand deposit to CO_2-enriched water for an extended duration prior to centrifuge testing.

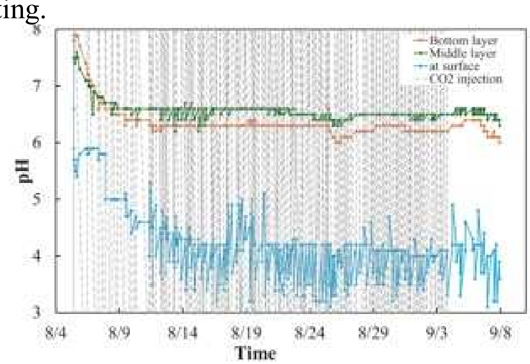

Figure 2 Temporal variation of pore-water pH at the different depths during 1 g carbonation

Figure 2 shows the resulting carbonation record, which presents the temporal evolution of pore-water pH at the surface, middle, and bottom layers, with dashed lines indicating CO_2 injection events. An initial rapid decrease in pH is observed at all depths, confirming effective dissolution of CO_2 and initiation of carbonation reactions. With continued exposure, the response becomes depth dependent: the surface layer exhibits the largest and most persistent pH reduction (approximately pH 3.5–4.5), while the middle and bottom layers stabilise at higher pH values (approximately pH 6.1–6.6), reflecting attenuation of carbonation with depth due to transport limitations and carbonate buffering. Short-term pH fluctuations coincide with CO_2 injections, whereas the overall stabilisation trend indicates progressive chemical equilibration of the soil. These results demonstrate successful and non-uniform carbonation of the calcareous sand prior to centrifuge zone load testing.

Centrifuge zone load testing revealed a change in the mechanical response of the calcareous sand following carbonation. Compared to the non-carbonated condition, the carbonated soil exhibited reduced stiffness and a lower resistance to applied loading (based on stress-settlement behaviour), indicating degradation of load-transfer mechanisms at particle contacts. These observations are consistent with carbonation-induced dissolution and surface alteration of $CaCO_3$ grains, which weaken interparticle bonding and reduce the soil's bearing capacity. The centrifuge results therefore confirm that carbonation leads to a measurable deterioration in the mechanical behaviour of calcareous sands, even when chemical alteration is induced prior to dynamic scaling.

4 CONCLUSIONS

This study investigated the process of carbonation on reclaimed calcareous sand by inducing controlled carbonation at 1 g and subsequently evaluating soil behaviour using centrifuge-based zone load testing. Continuous pH monitoring confirmed effective and depth-dependent carbonation, with stronger chemical alteration near the surface and attenuated effects at depth. Zone load test results showed reduction in stiffness and bearing capacity after carbonation, indicating that carbonation-induced dissolution of calcium carbonate weakens interparticle contacts and increases soil compressibility. These findings highlight the importance of accounting for long-term carbonation effects when assessing the performance of reclaimed coastal infrastructure.

ACKNOWLEDGEMENTS

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REFRENCES

Giretti, D Ã, V Fioravante, K Been, and S Dickenson. 2025. "Mechanical Properties of a Carbonate Sand from a Dredged Hydraulic Fill." *Geotechnique* 68 (5): 410–20. https://doi.org/https://doi.org/10.1680/jgeot.16.P.304.

Opukumo, Alfred Wilson, Stephanie Glendinning, and Collin T Davie. 2024. "Collapse of Calcareous Silty Clay : Implication of Calcite Content and Wetting Fluid Type." *Geotechnical and Geological Engineering* 42 (1): 165–84. https://doi.org/10.1007/s10706-023-02563-w.