

CPT Response of Carbonate Sand in Abu Dhabi: Miniature Cone Penetrometer Tests and Numerical Simulation

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ABSTRACT: This study presents an investigation into Cone Penetration Test (CPT) responses in carbonate sands commonly found in reclaimed islands across Abu Dhabi in the United Arab Emirates (UAE). Interpreting CPT results in carbonate sands poses significant challenges due to their crushable and angular nature, which differs markedly from that of silica-based sands. To address these complexities, dredged carbonate sands were collected from reclamation sites in Abu Dhabi and transported to Khalifa University and KAIST in South Korea for detailed laboratory and numerical studies. A series of monotonic triaxial compression tests were conducted to characterize the mechanical behavior of the carbonate sands and calibrate constitutive models. In addition, miniature CPTs were performed in both calibration chamber and centrifuge facilities to replicate in-situ stress conditions and penetration mechanisms. These tests provided valuable insights into the stress-strain relations and penetration resistance of carbonate sands under controlled environments. The CPT responses observed in the experimental campaigns were interpreted using cavity expansion theory in conjunction with pertinent constitutive models tailored for carbonate sands. The simulation results demonstrate good agreement with experimental observations, successfully capturing the unique penetration characteristics of carbonate sands, such as compressive and crushing nature. This integrated experimental and numerical approach enhances the understanding of CPT behavior in carbonate sands and provides a more reliable framework for interpreting CPT data in reclaimed island developments in the UAE and similar regions. The outcomes of this study contribute to improving geotechnical site characterization and foundation design in carbonate-dominated ground conditions.

KEYWORDS: Carbonate sand, Constitutive model, Cavity expansion analysis, Miniature cone penetrometer test.

1 INTRODUCTION

In recent decades, numerous islands made of reclaimed ground have been constructed offshore of the United Arab Emirates (UAE) to facilitate the expansion of infrastructure and urban growth. These islands are typically composed of calcareous, or carbonate sands dredged from the adjacent seafloor. The sand particles consist of the skeletal remains of marine organisms, including shell fragments and coral debris. These materials are crushable and possess distinct mechanical properties compared to typical quartz-silica sands. The National Marine Dredging Company (NMDC), UAE has been actively involved in the reclamation and improvement of these islands, conducting extensive cone penetration tests (CPT) both pre- and post-ground improvement to ensure the strength and density of these deposits. The unique physical and mechanical properties of these sands present serious difficulties for geotechnical design, as correlations and models designed for silica sands are inapplicable. The importance of understanding the mechanical characteristics of these materials is crucial for ensuring the stability of artificial islands composed of carbonate sands.

This study reports on triaxial drained compression tests conducted on dredged carbonate sand from offshore projects in Abu Dhabi by varying relative density (D_r) and confining pressure (σ'_c). The stress-strain characteristics of this sand are investigated, including peak strength and deformation characteristics. The results highlight the distinctive behavior of carbonate sands, including the characteristic downward-hook shape in the stress-dilatancy relationship. The established NorSand constitutive model is extended by introducing a new

material parameter to model the unique stress-dilatancy relationship of the sand. The extended model is further applied to simulate the CPT behavior using spherical cavity expansion analysis. In addition, laboratory-scale miniature cone penetrometer tests are performed in both calibration chamber and centrifuge settings to establish correlations between CPT cone tip resistance and the mechanical properties of carbonate sand.

2 ABU DHABI CARBONATE SAND

The carbonate sand was sourced from Ghasha Island and Hudariyat Island, Abu Dhabi, UAE. These soils were transported to Khalifa University, UAE and Korea Advanced Institute of Science and Technology (KAIST), South Korea, for testing. Figures 1 and 2 show pictures of the samples from Ghasha and Hudariyat islands, respectively. Their grey-white colour indicates calcium carbonate (CaCO_3), the predominant mineral is CaCO_3 , constituting 93% of the total weight, classifying the soil as carbonate sand (Clark and Walker, 1977). Table 1 summarizes the basic properties of tested sands. Specific gravity (G_s) and void ratio are much higher for carbonate sand compared to silica sand. Scanning electron microscopy (SEM) analysis further revealed that sand particles are platy-angular in shape and contain abundant pores.

Table 1. Physical and mineralogical properties of tested sand

Parameter	Symbol	Ghasha Island	Hudariyat Island
Specific gravity	G_s	2.85	2.85
Max. void ratio	e_{max}	0.88	0.92
Min. void ratio	e_{min}	0.59	0.58

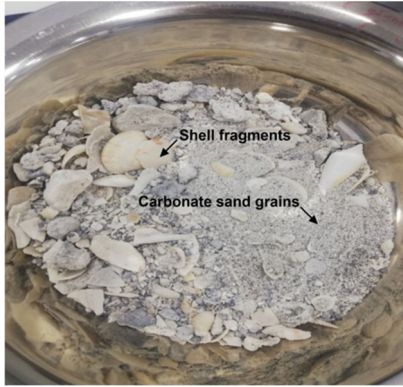


Figure 1. Photograph of carbonate sand from Ghasha Island at Khalifa University, UAE

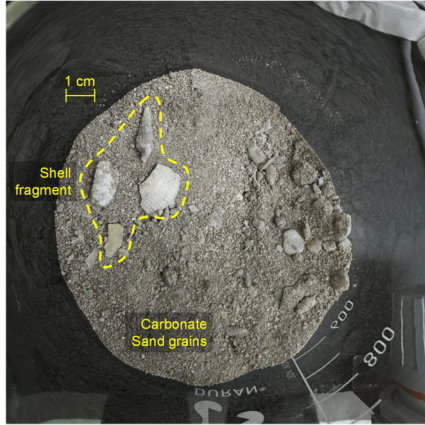


Figure 2. Photograph of carbonate sand from Hudariyat Island at KAIST, South Korea

3 CONSTITUTIVE MODELLING FOR CARBONATE SAND

Consolidated drained triaxial compression tests were performed on Abu Dhabi carbonate sand samples in the Geotechnical Materials laboratory at Khalifa University with varying D_r and σ'_c , isotropically consolidated at 30, 100, and 300 kPa. Three tests were conducted for each D_r level (loose, medium, dense) resulting in a total of nine tests. Loose specimens were prepared using the moist tamping method, while the dense specimens were prepared using the air pluviation method. The stress-dilatancy relationships, shown in Figure 3 for $D_r = 40\%$, exhibit a distinctive downward-turning hook characterized by initial contraction followed by dilation before reaching critical state. This behavior in carbonate sands has been observed in previous studies (Wang et al., 2022; Luo et al., 2023).

To capture this unique response, the NorSand model (Jefferies and Been, 2015) was extended by introducing a new stress-dilatancy relationship (Equation 1), where the slope between stress ratio (η) and dilatancy (D) follows $(1-\beta)$.

$$\eta = M_i - (1 - \beta) D \quad (1)$$

where M_i is the image stress ratio depending on soil state. The yield surface was derived using the normality rule, and the hardening law and plastic strain increments were modified to include β . The critical state was determined from laboratory experiments by extrapolating the volumetric strain until reaches a constant value. Model calibration was conducted based on peak and critical state responses from laboratory tests, with stiffness parameters evaluated numerically. Figure 4 demonstrates reasonable agreement between experimental and simulated stress-strain responses using the calibrated model (Nambiar and Kishida 2025).

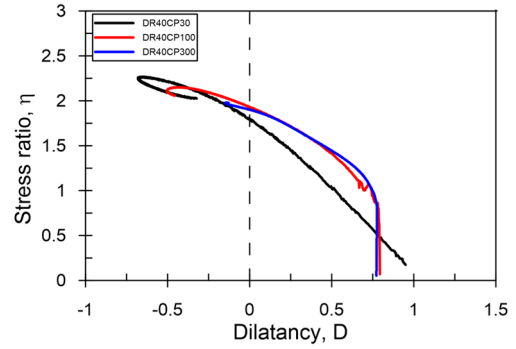


Figure 3. Stress-dilatancy relationship of tested sand.

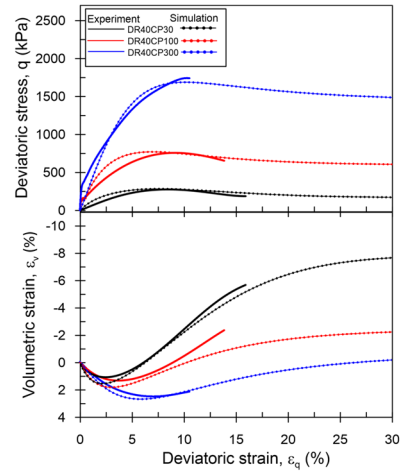


Figure 4. Comparison between simulated and experimental results.

4 MINIATURE CONE CALIBRATION CHAMBER TEST IN KHALIFA UNIVERSITY

A series of miniature cone penetrometer tests were performed on the specimens under different D_r prepared in a calibration chamber of 100 mm in diameter and 200 mm in height. For this purpose, a miniature cone penetrometer was designed and developed by adapting an existing GCTS triaxial compression cell (Damavandi and Sadrekarimi, 2015). To this end, a stainless-steel cone was fabricated with a diameter of 6 mm and a length of 100 mm. The top cap of the triaxial cell was modified by drilling a central hole to allow the cone to pass through. The miniature cone was connected to an internal load cell, which was subsequently interfaced with a data acquisition system and recorded the cone tip resistance (q_c) directly using LabVIEW software. A rubber O-ring was inserted in between the cone tip and outer hollow shaft to ensure q_c was effectively transmitted to the internal load cell. Further, an external load cell was used to measure the total cone resistance (q_t) and sleeve friction (f_s) through GCTS software, where q_t is defined as the total cone resistant force divided by the cone base area.

Figure 5 shows the test setup. Cylindrical soil specimens were prepared using air pluviation to achieve the desired D_r . After preparation, each specimen was isotropically consolidated to the target consolidation pressure. Following consolidation, the miniature cone was pushed into the specimen to a penetration depth of 40 mm at a rate of 10 mm/min. Figure 6 shows the q_c profiles with penetration depth for different initial void ratio and chamber pressures. The steady state tip resistance after a penetration depth of 30 mm is considered as the representative q_c at the specific confining pressure. To account for boundary effect due to the relatively low chamber to cone diameter ratio ($D/d=16.67$), the measured tip resistance was corrected using the equation by Kulhawy and Mayne (1990).

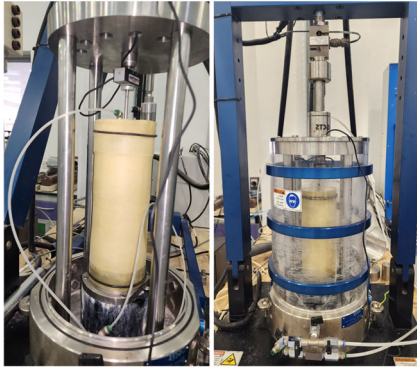


Figure 5. Calibration chamber set up for miniature CPT using a GCTS triaxial testing system, Khalifa University.

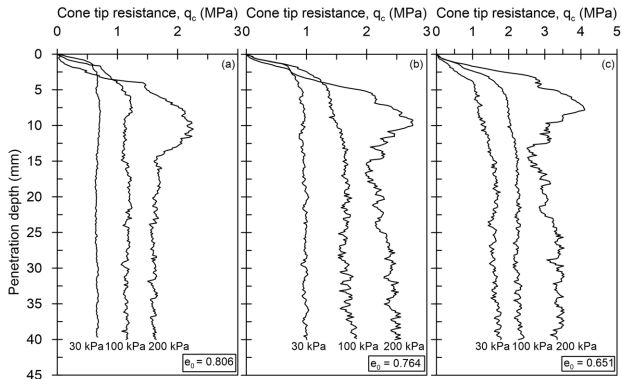


Figure 6. Cone tip resistance (q_c) profiles with penetration depth.

5 MINIATURE CONE PENETRATION TESTS IN A CENTRIFUGE

A series of miniature cone penetrometer tests were performed in the centrifuge facility at KAIST (Figure 7). The CPT was conducted using a miniature cone with a diameter of 12 mm and a length of 380 mm, performed four times at a centrifugal acceleration level of 60g. The miniature cone was equipped with four strain gauges at the cone tip, configured as a load cell using a Wheatstone bridge circuit to measure the cone tip resistance. The centrifuge CPTs were carried out with proper consideration of the conditions that could influence q_c , including penetration rate, distance between CPTs, boundary conditions from the container wall, and particle size-cone diameter ratio (Gui et al., 1998; Bolton et al., 1999; Bałachowski, 2007). The soil model was prepared by weakly compacting, to prevent particle crushing, carbonate sand from Hudariyat Island into a rectangular rigid container (length \times width \times height = 995 \times 995 \times 450 mm) to a height of 350 mm with an initial D_r of 43.8% ($\gamma_d=1.804 \text{ Mg/m}^3$), followed by saturation achieved by positioning the water level 10 mm above ground surface.

During the tests, q_t and q_c were measured at the top and tip of the cone, respectively, while f_s was calculated using the difference between the above observed values. The test results shown in Figure 8 indicate that q_t reaches approximately 4–6 MPa, q_c 4–5 MPa, and f_s converges to 0 or exhibits negative values depending on the penetration location. The penetrations were conducted until an 18 m prototype depth, which can be influenced by bottom boundary. Specifically, the centrifuge CPT, similar to the chamber CPT, exhibited a zone where q_c stabilizes following a certain penetration depth, occurring at approximately 7–14 m depth, and at greater depths (14–18 m), q_c was observed to increase again. This increase is attributed to the influence of the bottom boundary.



Figure 7. Centrifuge cone penetration tests carried out at KAIST.

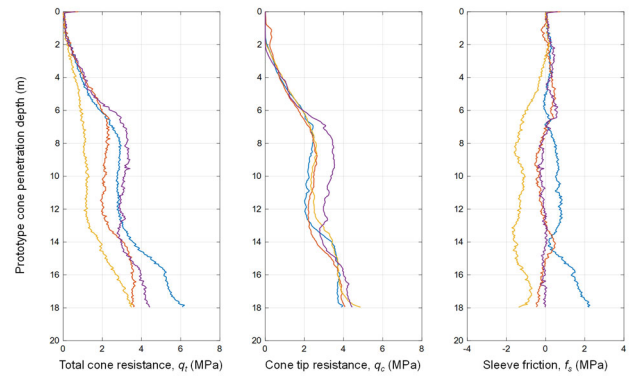


Figure 8. Cone tip resistances (q_c) from centrifuge CPTs. Herein, four penetration results are shown.

6 SPHERICAL CAVITY EXPANSION ANALYSIS

Drained spherical cavity expansion analysis was carried out using the extended NorSand model developed for this study, following the approach by Chen and Aboulseiman (2013). To this end, the cavity is expanded by monotonically increasing its radius until constant pressure is reached. This pressure, known as cavity limit pressure p_L , is directly converted to q_c measured in CPT with an analytical formulation (Yu 2000). Figure 9 presents the results of spherical cavity expansion in carbonate sand from Ghasha Island under drained conditions. Evidently, p_L increases with both relative density and confining pressure. A correlation proposed by Jamiolkowski et al. (2001) is included in the figure to model this relationship.

Normalized p_L by spherical cavity expansion (Q_{SCE}) was calculated using Equation (2). Similarly, normalized q_c by miniature CPT in calibration chamber (Q_{CC}) were computed using Equation (3). Figure 10 shows the comparison between Q_{SCE} and Q_{CC} against the initial state parameter (ψ_0). Both data exhibit clear linear trends between Q and ψ_0 , presenting strong correlation between these variables. Equation (4) presents the regression model, determining the conversion factor from Q_{SCE} to Q_{CC} . Using this equation, normalized cone tip resistance can be determined for various initial states using spherical cavity expansion analysis, enabling a more accurate prediction of CPT response in carbonate sand. Figure 11 presents stress-normalized cone resistance (q_{tI}) calculated using Equation (5) vs. D_r for carbonate sands. Cavity expansion predictions are also shown as a shaded region using the extended NorSand model, which was calibrated for Abu Dhabi carbonate sands. The experimental conversion factor from p_L to q_c given in Equation (4) is also applied. The results indicate that cavity expansion analyses can reasonably predict the q_{tI} using the calibrated carbonate sand models adjusted with the conversion factor from Equation (4).

$$Q_{SCE} = (p_L - p'_0) / p'_0 \quad (2)$$

$$Q_{CC} = (q_c - p'_0) / p'_0 \quad (3)$$

$$Q_{CC} = 0.3 Q_{SCE}^{1.6} \quad (4)$$

$$q_{t1} = (q_c - p_a) (\sigma'_v / p_a)^{-0.5} \quad (5)$$

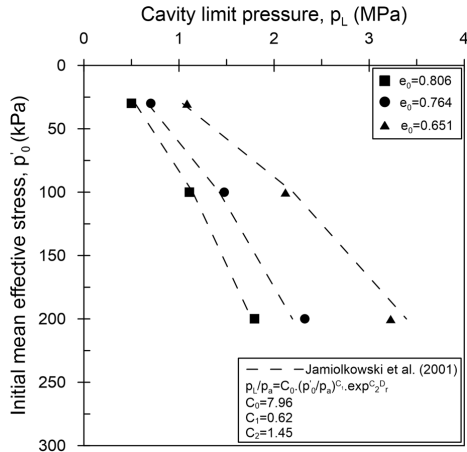


Figure 9. The relationship between cavity limit pressure and initial mean effective stress.

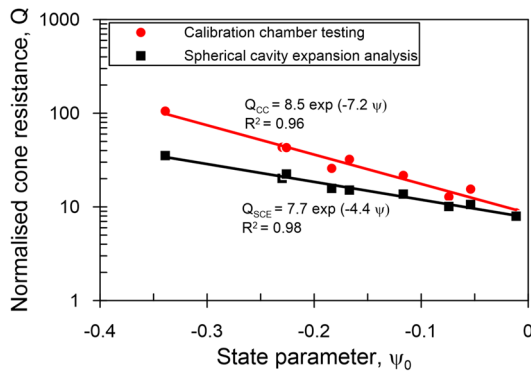


Figure 10. Comparison of cavity expansion and calibration chamber test results.

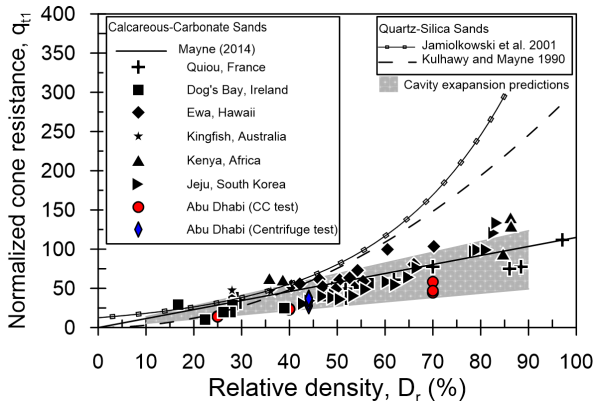


Figure 11. Normalized cone resistance versus relative density.

7 CONCLUSIONS

This study combined experimental investigations and numerical simulations to evaluate the mechanical and physical behavior of carbonate sand sourced from an artificial island in Abu Dhabi. To this end, consolidated drained triaxial compression tests were conducted using varying relative densities (D_r) and confining stresses (σ'_c), revealing a

distinctive stress–dilatancy response characterized by a downward-turning hook near the peak stress ratio. To capture this behavior, the NorSand model was extended with an additional material parameter and employed to simulate cone penetration using spherical cavity expansion analysis. Validation was carried out using miniature cone penetrometer tests conducted in both a triaxial calibration chamber and a centrifuge, with systematic variations in D_r and σ'_c . The results from the two experimental campaigns exhibited meaningful agreement, confirming the robustness of the testing methods. Additionally, a correlation was examined between the normalized cone tip resistance obtained from cavity expansion analysis and the miniature cone penetrometer tests. After applying a correction factor for limiting pressure, the predictions of cavity expansion theory closely align with the miniature cone penetrometer measurements.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

- Balachowski, L. (2007). Size effect in centrifuge cone penetration tests. *Archives of Hydro-Engineering and Environmental Mechanics*, 54(3), 161-181.
- Bolton, M. D., Gui, M. W., Garnier, J., Corte, J. F., Bagge, G., Laue, J., & Renzi, R. (1999). Centrifuge cone penetration tests in sand. *Geotechnique*, 49(4), 543-552.
- Clark, A.R. and Walker, B.F., 1977. A proposed scheme for the classification and nomenclature for use in the engineering description on Middle Eastern sedimentary rocks. *Geotechnique*, 27(1), pp.93-99.
- Damavandi-Monfared, S. and Sadrekarimi, A., 2015. Development of a Miniature Cone Penetrometer for Calibration Chamber Testing. *Geotechnical Testing Journal*, 38(6), pp.878-892. <https://doi.org/10.1520/GTJ20150036>.
- Ghahghazi, M. and Shuttle, D., 2008. Interpretation of sand state from cone penetration resistance. *Geotechnique*, 58(8), pp.623-634. <https://doi.org/10.1680/geot.2008.58.8.623>.
- Gui, M. W., Bolton, M. D., Garnier, J., Corte, J. F., Bagge, G., & Laue, J. (1998). Guidelines for cone penetration tests in sand. In *Centrifuge 98* (pp. 155-160).
- Jamiolkowski, M., Lo Presti, D.C.F., Manassero, M., 2003. Evaluation of relative density and shear strength of sands from CPT and DMT, in: *Soil Behavior and Soft Ground Construction*. pp. 201-238.
- Jefferies, M. and Been, K., 2015. *Soil Liquefaction: A Critical State Approach, Second Edition*. <https://doi.org/10.1201/b19114>.
- Kulhawy F.H and Mayne P.W, 1990. *Manual on Estimating Soil Properties for Foundation Design*. Cornell University, Ithaca: Geotechnical Engineering Group.
- Luo, M., Zhang, J., Liu, X. and Wu, C., 2023. Effect of Particle Breakage and Interlocking on Strength and Dilatancy Characteristics of Calcareous Sands. *KSCCE Journal of Civil Engineering*, 27(8), pp.3270-3284. <https://doi.org/10.1007/s12205-023-1470-5>.
- Nambiar, D. K. and Kishida, T., 2025. Modelling the stress–dilatancy behavior of carbonate sand in Abu Dhabi. *Can. Geotech. J.* 62, 1-15. <https://doi.org/10.1139/cgj-2025-0186>
- Wang, X., Shan, Y., Cui, J., Zhong, Y., Shen, J.-H., Wang, X.-Z. and Zhu, C.-Q., 2022. Dilatancy of the foundation filling material of island-reefs in the South China Sea. *Construction and Building Materials*, 323, p.126524. <https://doi.org/10.1016/j.conbuildmat.2022.126524>.
- Yu, H.S., 2000. *Cavity Expansion Methods in Geomechanics*. Springer Netherlands.