Liquefaction Susceptibility and Dynamic Properties of Calcareous Sands from Cabo Rojo, Puerto Rico

15 WCEE
LISBOA 2012

M.A. Pando
Department of Civil and Environmental Engineering, University of North Carolina at Charlotte, Charlotte, NC, USA, 28223, mpando@uncc.edu

E.A. Sandoval
Assistant Professor, School of Civil Engineering and Geomatics, University of Valle, Cali, Colombia, e-mail: eimar.sandoval@correounivalle.edu.co.

J. Catano
Geotechnical Project Engineer, Gannett Fleming Inc., Orlando, FL,USA, 32817
e-mail: jcatano@gfnet.com

SUMMARY:
This paper presents results from an experimental study on the liquefaction susceptibility and dynamic properties of uncemented calcareous sand from Cabo Rojo, southwest Puerto Rico. Calcareous sands are generally composed of skeletal remains of marine organisms and typically have unique particle characteristics such as particle shape, surface roughness, crushability, and intraparticle porosity. Furthermore due to their calcareous origin they have calcium carbonate content in excess of 90%.The experimental program involved a comprehensive set of undrained cyclic triaxial tests and resonant column tests on reconstituted samples of the Cabo Rojo calcareous sand and silica sand samples tested at similar conditions for comparison purposes.

Keywords: calcareous sands, liquefaction resistance, dynamic properties.

1. INTRODUCTION

Offshore and coastal construction activities in tropical regions have increased significantly over the past 30 years. The extents of calcareous deposits in these regions have led to a wealth of geotechnical investigations and research on calcareous and carbonate sands; the findings continue to reveal the unique engineering properties of these sediments. A large part of the Puerto Rican coast line is overlain by uncemented carbonate sands. The recent construction of port facilities and coastal developments on the island coupled with the high seismicity of Puerto Rico translates to the necessity to improve the understanding of the engineering behaviour of these Puerto Rican coastal soils.

Calcareous sands exhibit unusual engineering behaviour due to unusual particle properties: high susceptibility to particle crushing, local variations in particle sizes, shapes, and surface roughness, cementation, and pronounced internal porosity (Datta et al. 1982, Allman and Poulos 1988). For a select site located in the west coast of Puerto Rico a detailed experimental study was carried out. Resonant column tests were conducted to examine the dynamic behavior of a sedimentary calcareous sand of marine origin. Emphasis was placed on measuring the shear modulus G and damping ratio D, and the variation of these parameters with confining stress and shear strain. The dynamic properties of a silica sand with similar general particle shapes and particle size distribution were also measured. This was done to identify any differences in dynamic behavior that could arise due to the unique mineralogical and surface texture features of the calcareous grains. In particular, the extent of particle crushing was evaluated for selected specimens, due to the low hardness and high internal porosity of calcareous grains, which were anticipated to render unusual stress-dependent variations in G and D via particle crushing effects. Additionally the experimental study involved a series of monotonic and cyclic triaxial tests to assess stress-strain behaviour and liquefaction susceptibility of the calcareous sand. These test results were also compared with a silica sand with similar gradation and grain size characteristics. The main results of this study are summarized in this manuscript.

2. OVERVIEW OF SEISMICITY OF PUERTO RICO

The Caribbean island of Puerto Rico is located in a region of high seismicity. Major sources of seismic activity include several offshore active faults that surround the island as well as inland faults (Clinton et al. 2007). Most of the seismic activity of the area is produced by the convergence and lateral translation of the North American and Caribbean Plates beneath the Puerto Rico Platelet (Tuttle et al., 2003). Tuttle et al. (2003) have reported paleoliquefaction evidence of ancient liquefaction features in western PR near the city of Mayagüez suggesting that additional prehistoric earthquakes may have also occurred. The most damaging earthquake affecting Puerto Rico was the Aguadilla-Mayagüez Region earthquake of October 11, 1918 with a M_w =7.3 causing liquefaction, property damages of about $4 million (1918) dollars) and 116 people killed (Reid and Taber 1919). Despite its high seismic risk, research to adequately assess and mitigate earthquake hazard in Puerto Rico lags behind other seismically-active regions of the US, particularly quantification of expected ground motions and liquefaction susceptibility. The work presented in this paper is related to quantification of ground motions and liquefaction potential of calcareous sand deposits located in Western Puerto Rico, as well as studying their stress-strain behaviour and dynamic properties.

3. BACKGROUND ON CALCAREOUS SANDS

3.1. Index properties, stress-strain behaviour, and dynamic properties

Calcareous soils may be categorized by the type of formation mechanism. Sedimentary calcareous soils are formed in marine environments from the skeletal remains of corals, shells, and algae, and cover most coastal plains in tropical regions and continental ancient marine environments (Chaney et al. 1982). Non-sedimentary calcareous soils are derived from carbonate-rich materials through (1) weathering and/or (2) precipitation, and are found in arid and semi-arid regions (Demars and Chaney, 1982). Of particular importance to this research are sedimentary carbonates for which diagenesis and resulting grain mineralogy are influenced by the depth of the water column (Morse and Mackenzie 1990, Chaney et al., 1982, Morelock and Ramirez, 2004). In shallow water, carbonates are generally dominated by aragonite followed by magnesium-rich calcites. In deep water, carbonates are composed of calcite with low magnesium content. Grain characteristics are relevant: calcareous grains have unique shape, surface texture, and internal porosity features that play an important role in defining grain crushing and media compressibility (Golightly and Hyde, 1988). In general, there are two types of carbonate grains: skeletal and non-skeletal. Skeletal grains are formed as internal or external skeletal units of marine organisms. Non-skeletal grains are formed by physical and chemical processes, including bio-chemical and physico-chemical precipitation, rock erosion, and comminution (Morelock and Ramirez, 2004).

The geotechnical research of calcareous soils has increased over the last few years due to the increased offshore activity in areas of the world consisting of carbonate sediments. In addition, these soils warrant special consideration due to their unique characteristics (Allman and Poulos, 1988).

In terms of index properties, calcareous sands typically present higher specific gravities and void ratios than quartz silica sand (Morioka and Nicholson, 2000). The higher specific gravity values are due to their mineralogy composition which usually includes minerals such as calcite (specific gravity, G_s of 2.75) and aragonite (G_s = 2.95). Siliceous minerals, on the other hand, are less heavy, since they typically include quartz which is a mineral with a specific gravity value of 2.65.

Void ratios in silica sands typically range between 0.43 and 0.85. Void ratios of calcareous sands with large amounts of biogenic grains can be much higher than those of silica sands with similar skeletal arrangements. This is due to void ratio values of calcareous sands being the sum of two components: the regular void ratio related to the skeleton structure and the void ratio related to the grain voids. Engineering behavior may be difficult to infer from total void ratio values. A listing of typical specific gravity and void ratio values for selected calcareous sands is presented in Table 3.1.

Susceptibility to crushing is another very important consideration for calcareous sands since it highly influences their shear strength and geotechnical behavior. For example, Datta et al. (1982) found that crushing significantly reduces the drained angle of shearing resistance. Crushability in calcareous sands may mask or inhibit any tendency to dilate during shearing of these soils, which leads to lower lateral stresses in the ground, and consequently result in a less stiff response (Hull et al., 1988). Datta et al. (1982) found that the susceptibility to crushing is primarily related to the nature of the grains of calcareous sands. They determined that susceptibility to crushing increases with an increase in: (1) the amount of grains having large intraparticle voids; (2) the amount of thin-walled shell fragments; (3) the angularity of grains; (4) the coarseness of grains; and (5) the uniformity of its gradation.

Table 3.1. Typical index and dynamic properties of some calcareous sands.

Location	Country	$CaCO_3$ (%)	G_s (1)	e_{max} (2,4)	e_{min} (3,4)	Reference
Kingfish B.	Australia	84	2.75	1.12	1.48	Morioka (1999)
Bass Strait	Australia	62-88	2.73	1.13	0.54	Hull et al., (1988)
North Ranking	Australia	91	2.77	1.87	1.15	Hull et al., (1988)
Bombay Mix	India	70-80	2.80	0.75	1.07	Golightly and Hyde (1988)
West Coast	India	>85	2.79 to 2.81	0.77	1.39	Morioka (1999)
Lakshdweep Island	India	>85	2.78	0.8	1.2	Morioka (1999)
Florida	USA	92	2.84	1.06	1.44	Morioka (1999)
Dry Tortugas, Florida	USA	93	2.71 to 2.86	1.0	1.6	Pizzimenti (1996)
Dogs Bay	Eire	85-95	2.75	0.98	1.83	Golightly and Hyde (1988)
Ballyconeely	Eire	90-95	2.72	1.62	1.98	Golightly and Hyde (1988)
Guam Island	Guam	90	2.8	1.12	1.36	Morioka (1999)
Waikiki Beach	Hawaii	>90	2.79	1.12	1.69	Morioka (1999)
Ewa Plains	Hawaii	98	2.72	0.66	1.30	Morioka (1999)

Notes: (1) G_s: Specific gravity,
(2) e_{max}: Maximum void ratio
(3) e_{min}: Minimum void ratio..
(4) No mention made whether values include both inter- and intra-particle voids or only interparticle voids.

Based on the literature review carried out for this study, it is possible to conclude that calcareous and silica sands behave differently when subjected to mechanical deformation. For instance, calcareous sands typically present a higher friction angle than silica sands with similar relative densities, however, they tend to exhibit a much less stiff response than silica sand, primarily due to particle crushing (Hull et al., 1988). Three factors were reported in the literature as being the main causes for anomalous behavior of calcareous sands are: (1) the susceptibility of calcareous grains to crushing when stressed; (2) particle characteristics such as the variation in size and shape, and the presence of intraparticle voids; and (3) the cementation and fabric related to its carbonate materials.

Regarding dynamic properties of these sands, Lo Presti et al. (1993) reported on the monotonic and cyclic loading behavior at small strains of Quiou calcareous sands and Ticino silica sand. The influence of confining pressure, shear strain levels and type of loading on the shear modulus were analyzed. They found that at the same confining stress, the Ticino silica sand exhibited small-strain shear modulus values (G_{max}) higher than those for the Quiou calcareous sand. The elastic threshold shearing strains for both sands were less than about 0.001%. The shear moduli obtained from the cyclic tests were 20% greater than those from the static monotonic loading tests, for Quiou calcareous sands. They concluded that this difference is due to the sand crushability caused by the load repetition in cyclic tests. This behavior was not observed for Ticino silica sand. Further details on dynamic properties of the uncemented Quiou sand was provided by Fioravante et al. (1994). They reported two main findings for the dynamic properties of calcareous Quiou sand: (a) experimental data showed the influence of stress history (i.e., overconsolidation ratio, OCR) on the shear deformational behavior of Quiou sand at very small strains; and (b) the number of inter-particle contacts affects the stiffness of calcareous sands. The increase of inter-particle contacts was caused by the crushing of particles and their re-arrangement.

3.2. Liquefaction studies

For background and comparison purposes, Table 3.2 provides a brief summary of the published literature on liquefaction resistance of calcareous sands. The studies listed here were selected due to the similarity in scope and testing methodology implemented in this study. The cyclic stress ratios (CSR) values used in these experiments ranged between 0.13 and 0.45, and sand samples were prepared with relative densities (D_r) between 59 and 65%. Based on the limited results presented in this table it appears that most calcareous sands have a greater susceptibility to liquefaction than Ottawa silica sand samples tested under similar conditions. This with the exception to the finer Waikiki A sand tested by Flynn and Nicholson (1997). Clearly more tests are required to confirm these preliminary observations.

Table 3.2. Summary of previous studies on the liquefaction susceptibility of calcareous sands which used cyclic triaxial testing

Name of calcareous sand (Reference)	D_{50} (mm)	D_{10} (mm)	C_u	D_r (%)	e_{min}	e_{max}	G_s	Cyclic Triaxial Results at σ'_c = 100 kPa Cycles to liquefaction (N_f) for CSR = 0.3
Kurkar (Frydman et al, 1980)	0.10	-	-	59 63	-	-	-	3
Waikikí A (Flynn and Nicholson, 1997)	0.21	0.14	1.57	65	1.12	1.69	2.79	34
Waikiki B (Flynn and Nicholson, 1997)	0.74	0.18	5.05	65	0.66	1.303	2.71	2
Dog Bays (Hyodo et al, 1998)	0.22	0.11	2.36	60	1.61	2.45	2.72	~1
Ewa Plains (Morioka and Nicholson, 2000)	0.82	0.20	4.1	65	0.66	1.30	2.72	2
Ottawa silica sand (used in this study)	0.75	0.65	2.1	68	0.50	0.78	2.65	3

4. CABO ROJO CACAREOUS SANDS

The calcareous sand used in this study was retrieved from a beach in Cabo Rojo, western Puerto Rico. These calcareous sands have grains composed of marine organisms as illustrated in the micrographs shown in Figure 4.1. An important unique characteristic of these sands is their intra-particle void structure, which combined with the skeletal void ratio can result in total void ratios as high as e = 2.1. In this figure it is possible to visualize the unique biogenic characteristics of the sand grains and their high intra-particle porosity, surface roughness, etc. The absence of major rivers in the sampling site of this calcareous sand favored the presence of uncontaminated, high carbonate content particles, with aragonite and calcite as the principal carbonate minerals (91% to 97% by mass, as obtained via X-ray diffraction and thermo-gravimetric analyses). Due to their mineralogical composition, these calcareous sands have a high specific gravity of about 2.84, which is considerably larger than the typical specific gravity value of 2.65 for silica sands. It should be noted that both calcite and aragonite are $CaCO_3$; however these minerals exhibit different crystallographic structures and dissimilar cleavage planes, which makes aragonite a heavier mineral when compared to calcite.

5. COMPARISON STUDY OF DYNAMIC PROPERTIES

The dynamic properties of the Cabo Rojo calcareous sand were compared with a silica sand obtained from a Transit-Mix plant in South Bend, Indiana. The gradation of the comparison silica sand was made to match the grain size distribution of the calcareous sand. The objective of including a comparison silica sand with the same gradation was to allow studying the influence of the unique grain characteristics of the Puerto Rico calcareous sands (e.g., particle shape, texture, intra particle porosity, and mineralogy). A summary of the main index properties of the two tests sands is presented in Table 5.1. This table shows that the Cabo Rojo calcareous sand has a specific gravity (Gs) of 2.86 which is higher than the 2.7 value for the comparison silica sand. This is mainly related to the mineralogy of the Cabo Rojo calcareous sand which not only includes calcite and some aragonite. In contrast, the maximum and minimum unit weight values for the Cabo Rojo calcareous sand were lower than the corresponding values of the comparison silica sand compacted at a similar state. These lower values are related to the higher void ratios obtained in both the maximum and minimum density states. Hence, the void ratio values reported in Table 5.1 for the calcareous sand are actually the sum of the void ratio of the skeleton structure (conventional void ratio) and the void ratio corresponding to the void spaces inside the grains. Table 5.1 also shows the calcium carbonate content of both sands, which was used to confirm the calcareous nature of the Cabo Rojo sand. More details on the mineralogy of both test sands can be found in Cataño and Pando (2010).

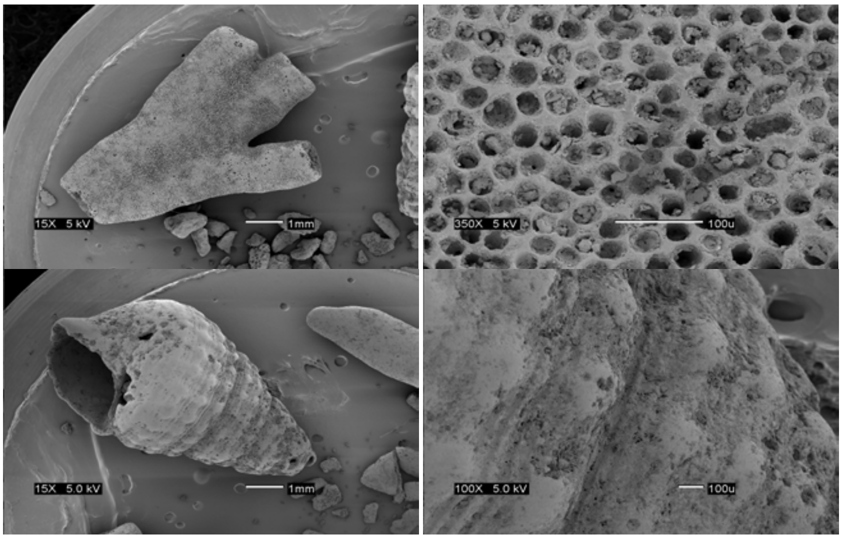


Figure 4.1. SEM micrographs of biogenic grains of the Cabo Rojo calcareous sand

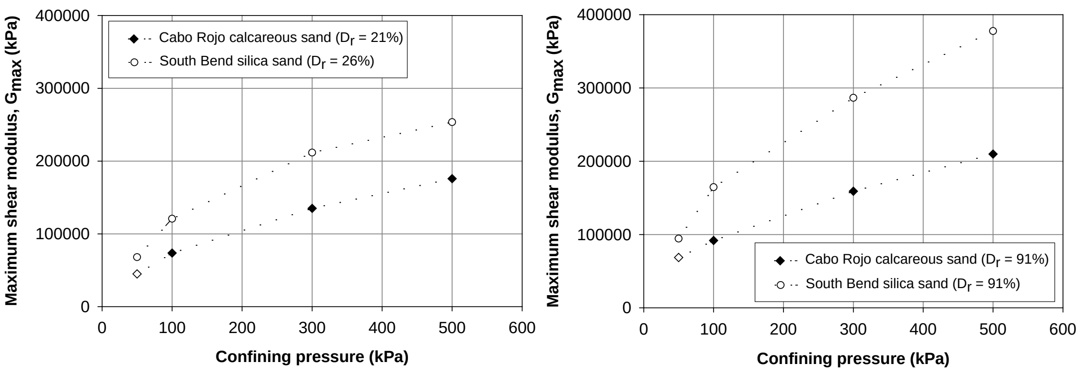
The dynamic properties of the calcareous and silica sands were assessed using resonant column (RC) tests as described in Cataño and Pando (2010). The RC specimens were prepared at three relative densities: minimum (21% to 26%), medium (58% to 59%), and maximum (91%), and at four levels of effective confining pressures (50, 100, 300, and 500 kPa).

The RC test results showed that, as expected for conventional sands, the dynamic properties of the Cabo Rojo calcareous sand exhibited strong shear strain dependency for strain levels beyond the elastic threshold strain. Below the threshold strain, shear modulus values (G_{max}) and damping ratios (D_{min}) remained almost constant, and basically independent of the strain level. With increasing strain beyond of the elastic threshold, the shear modulus decreases and the damping ratio increases, which demonstrates the non-linear behavior of Cabo Rojo sand for medium to large strains. The RC testing also show that the G_{max} of the Cabo Rojo sand increases with the isotropic confining stress. Variation with confining pressure of maximum shear modulus (G_{max}), for both test sands, is shown in Figure 5.1 for the minimum and maximum relative densities. This figure shows greater G_{max} values for the South Bend silica sand compared to the Cabo Rojo calcareous sand, which indicates a less stiff dynamic response for the calcareous sand. Values of G_{max} between 45 and 210 MPa were obtained for the calcareous sand, while G_{max} values of the silica sand varied from 68 and 378 MPa.

Table 5.1. Index properties of test sands in dynamic properties study.

Parameter	Calcareous sand	Silica sand	Method
D_{10} (mm)	0.20	0.20	ASTM D422-63
D_{30} (mm)	0.30	0.29	
D_{50} (mm)	0.38	0.36	
D_{60} (mm)	0.42	0.40	
G_s	2.86	2.70	ASTM D5550
e_{max}	1.71	0.74	ASTM D4254
γ_{min} (kN/m^3)	10.5	15.2	
e_{min}	1.34	0.50	ASTM
γ_{max} (kN/m^3)	12.1	17.6	
$CaCO_3$ (%)[1]	92.8	10.6	TGA[2]

Notes: (1) $CaCO_3$: Calcium carbonate content

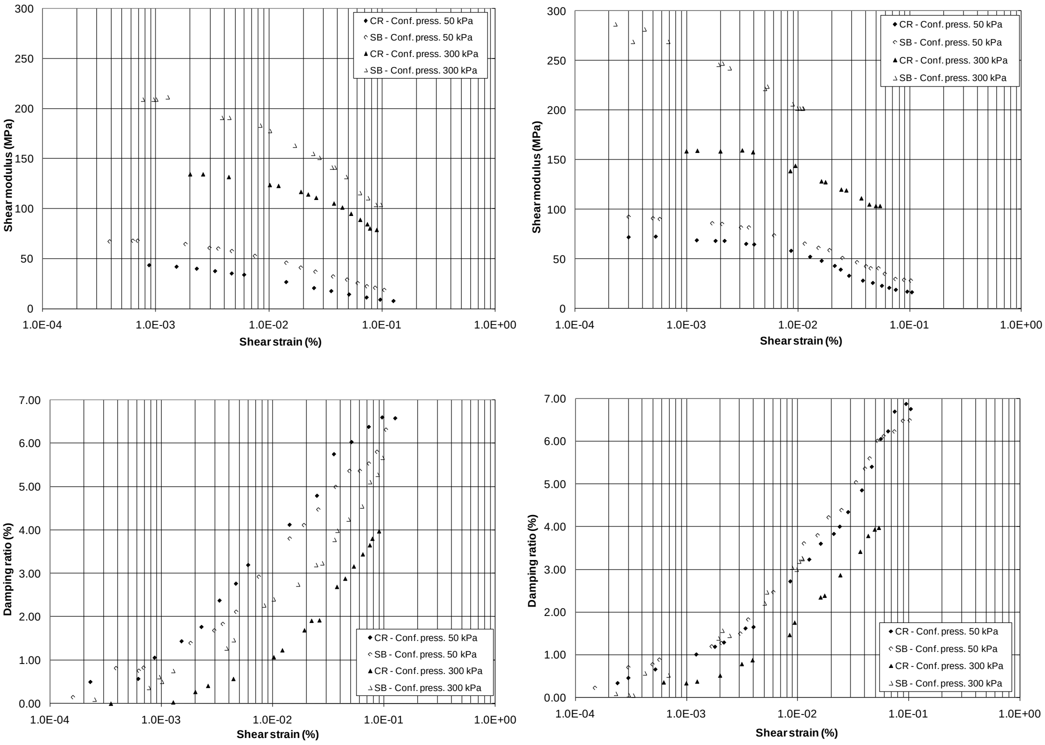


a) low relative density (D_r = 21 to 26%) **b) high relative density (D_r = 91%)**

Figure 5.1. Comparison of maximum shear modulus for both sands.

Comparison of the variation in shear modulus (G) and damping ratio (D) values with shear strain (γ) for both test sands is shown in Figure 5.2, at confining pressures of 50 and 300 kPa, for the minimum and maximum relative densities. This figure indicates that silica sand has a greater stiffness shear modulus than the calcareous sand. This trend was observed for specimens prepared at low and high relative densities. Figure 5.2(a) shows that at confining pressures of 50 kPa, calcareous sand specimens presented greater damping ratio values than silica sand specimens under similar density and stress conditions. The opposite situation was observed for confining pressures of 300 kPa, where silica sand exhibited larger damping ratio values than calcareous sand. However, for higher densities (Figure 5.2(b)), contrary to the Cabo Rojo calcareous sand, the South Bend silica sand did not present a notable range of damping ratio values, indicating little influence of the confining pressure.

This component of the study revealed important differences in the dynamic behavior measured for the two tests sands. Under similar relative densities and confining stress levels, the calcareous sands were found to be less stiff than the comparison silica sands in terms of G_{max} and G vs γ. However, no clear pattern was observed in terms of the material damping behavior, where the Cabo Rojo calcareous sand exhibited a higher dependency on confining pressures than the comparison silica sand.



a) low relative density (D_r = 21 to 26%) **b) high relative density (D_r = 91%)**

Figure 5.2. Dynamic properties as a function of shear strain for both sands at a low relative density**.**

6. LIQUEFACTION SUSCEPTIBILITY STUDY

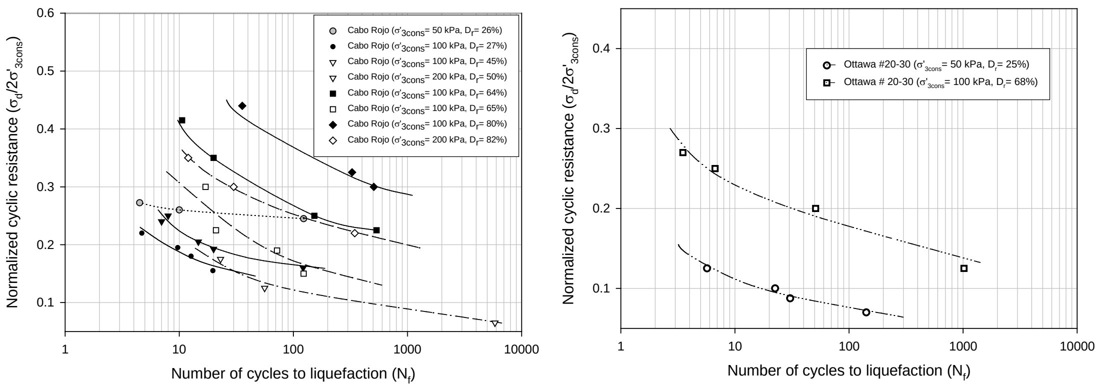
The liquefaction susceptibility of the Cabo Rojo calcareous sand was also investigated as part of this study. The test sand was retrieved from the same beach but at a few months later. The calcium carbonate content for this batch of calcareous sand was measured to be at least 91%. The main index properties of the Cabo Rojo sand and the Ottawa sand used for comparison purposes are listed in Table 6.1. It is important to note that besides the different mineralogy, these two sands also have important difference in terms of grain characteristics and particle size distributions.

Cyclic triaxial test specimens were prepared using the “moist tamping” technique using five layers and the under-compaction method suggested. Prepared samples were approximately 102 mm high and with a 51 mm diameter. The relative densities ranged between 20% and 75% prior to consolidation, and between 29% and 83% after isotropic consolidation. To achieve saturation, specimens were first flushed with carbon dioxide (CO_2) and then flushed with de-aired water in an attempt to displace any entrapped air. After flushing samples with CO_2 and de-aired water, saturation process was completed using the standard back pressure method. Once sample saturation was ensured, specimens were isotropically consolidated under three different effective stress levels (50, 100, and 200 kPa). The isotropically consolidated samples were subjected to stress-controlled cyclic triaxial tests at a frequency of 1 Hz.

In this study, the number of load cycles to liquefaction in response to the applied Cyclic Stress Ratio (CSR), were investigated. For each relative density and effective consolidation stress level, between three and five cyclic triaxial tests were performed at different CSR levels. For each CSR level, the number of cycles required to produce liquefaction in the sample was recorded. For the cyclic triaxial testing liquefaction triggering criterion was defined as the condition where zero effective stress was reached (i.e., the excess pore pressure was equal to the consolidation effective stress) or when the double amplitude axial strain was ±5%. In this way the test results allowed the development of CSR curves for each relative density and effective consolidation stress level. A summary of the CSR curves obtained for the Cabo Rojo calcareous sand is presented in Figure 6.1. For comparison purposes, Figure 6.1also shows select CSR curves obtained with Ottawa silica sand samples.

Table 6.1. Summary of index properties for the test sands used in the liquefaction study

Parameter	Cabo Rojo calcareous sand	Ottawa # 20-30 silica sand	ASTM Standard
D_{10} (mm)	0.24	0.65	ASTM D422-63
D_{30} (mm)	0.30	0.71	
D_{50} (mm)	0.37	0.75	
D_{60} (mm)	0.41	0.78	
C_u	1.75	2.1	
C_c	0.94	1.1	
G_s	2.84	2.65	ASTM D854
γ_{min} (KN/m^3)	9.1	14.6	ASTM D4254
e_{max}	2.07	0.78	
γ_{max} (KN/m^3)	11.1	17.3	ASTM
e_{min}	1.51	0.50	



a) Cabo Rojo calcareous sand **b) Ottawa silica sand**

Figure 6.1. Cyclic resistance curves for Cabo Rojo calcareous and Ottawa silica sand

6.1. Influence of relative density in liquefaction resistance

Liquefaction resistance was found to increase with increasing relative density, as is illustrated in Figure 6.2, which shows CRR curves for the Cabo Rojo calcareous sand tested at different relative densities, with all samples isotropically consolidated to an effective stress of 100 kPa.

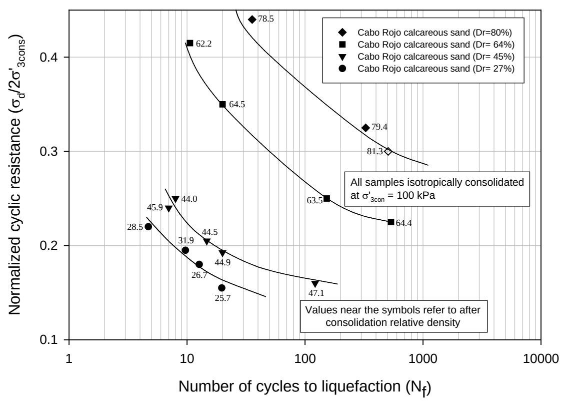
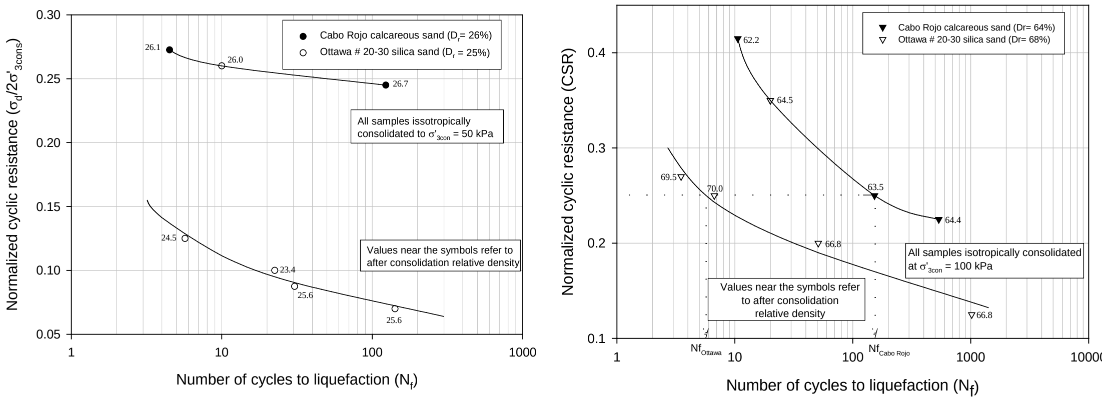


Figure 6.2. Cyclic resistance curves for Cabo Rojo sand at similar consolidation stress

6.2. Comparison of CRR curves for Cabo Rojo calcareous and Ottawa silica sand

Comparison of the liquefaction resistance of the Cabo Rojo calcareous sand and the Ottawa silica sand is shown in Figure 6.3(a) for samples prepared at a loose state (D_r: 23 – 27%), and isotropically consolidated to an effective stress of 50 kPa. A similar comparison is presented in Figure 6.3(b) for samples prepared at a medium dense state (D_r : 64 – 68%), and consolidated to 100 kPa. From these figures, it can be seen that the Cabo Rojo calcareous sands in general exhibits a much higher liquefaction resistance than the Ottawa silica sands, prepared and tested under similar relative densities and effective consolidation stresses.



a) low relative density (D_r = 23 to 27%) **b) medium relative density (D_r = 64 to 68%)**

Figure 6.3. Cyclic resistance curves for the Cabo Rojo and Ottawa sands

6.3. Comparison of CRR curves for Cabo Rojo and other calcareous sands from previous studies

Liquefaction resistance of calcareous sands from other regions of the world were summarized in Table 3.2. Figure 6.4 compares the CRR curves obtained from this study for the Cabo Rojo calcareous sand with results reported for other calcareous sands tested at a medium dense state D_r : 59 – 65%, and isotropically consolidated to an effective stress of 100 kPa. From this figure it can be seen that the Cabo Rojo calcareous sands exhibited higher liquefaction resistance than other calcareous sands tested in previous studies under similar conditions and test procedures.

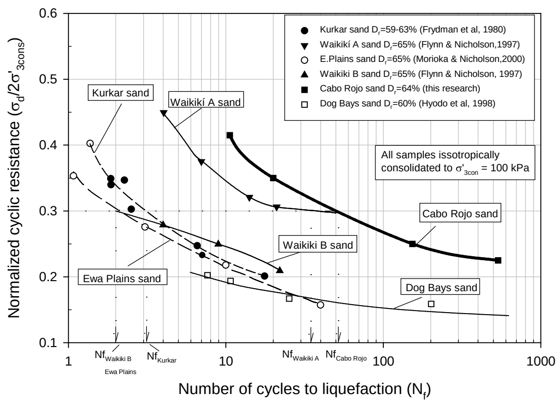


Figure 6.4. Comparison of cyclic resistance curves for Cabo Rojo and other calcareous sands

7. SUMMARY AND CONCLUSIONS

This study revealed that the Cabo Rojo calcareous sand exhibited a different geotechnical behavior when compared to conventional silica sand of similar particle size and gradation. In terms of dynamic properties, the Cabo Rojo calcareous behavior was found to have important differences. Under similar relative densities and confining stress levels, the calcareous sands were found to be less stiff than the comparison silica sand in terms of G_{max} and G vs γ. However, no clear pattern was observed in terms of the material damping behavior, where the Cabo Rojo calcareous sand exhibited a major dependency on confining pressures than the comparison silica sand.

The cyclic triaxial test results also revealed important differences between the response of the Cabo Rojo calcareous sand and samples prepared with Ottawa silica sand tested under similar conditions. Cabo Rojo calcareous sands exhibited a greater liquefaction resistance than Ottawa silica sand, tested at similar relative densities and consolidation effective stresses. Furthermore, the Cabo Rojo calcareous sands was found to exhibit larger liquefaction resistance compared to published results for calcareous sands from other regions of the world.

The differences in geotechnical behavior of the Cabo Rojo calcareous sand are highly related to the presence of particles of biogenic nature, with important differences in mineralogy, particle shape and porosity than the conventional silica sand. The differences in geotechnical behavior of the Cabo Rojo calcareous sand are in agreement with the findings of the literature review for other calcareous sands. Given the important differences in dynamic and liquefaction behavior of the Cabo Rojo calcareous sand, special considerations must be taken in the design and construction of coastal structures on these sand deposits. Therefore the applicability of conventional design methodologies used in geotechnical earthquake engineering analysis and design for this type of sand deposits must be evaluated based on project specific requirements and considerations.

REFERENCES

Allman, M. A., and Poulos, H. G. (1988). “Stress-strain Behavior of an ArtificiallyCemented Calcareous soil”. Engineering for Calcareous Sediments, Vol. 1. Balkema, Perth, 69-78.

Cataño, J. and Pando, M.A. (2010). “Static and Dynamic Properties of a Calcareous Sand from Southwest Puerto Rico”. ASCE, GeoFlorida. West Palm Beach, FL, USA.

Chaney, R. C., Slonim, S. M., and Slonim, S. S. (1982). “Determination of CalciumCarbonate Content in Soils”. Geotechnical Properties, Behavior and Performance ofCalcareous Soils, ASTM STP 777, 3-15.

Datta, M., Gulhati, S. K., and Rao, G. V. (1982). “Engineering Behavior of Carbonate Soils of India and Some Observations on Classification of Such Soils”. ASTM STP 777, 113-140.

Demars, K. R., and Chaney, R. C. (1982). “Symposium Summary” GeotechnicalProperties, Behavior and Performance of Calcareous Soils, ASTM STP 777, 395-404.

Fioravante, V., Capoferri, R., Hameury, O., and Jamiolkowski, M. (1994).“Deformational Characteristics of Uncemented Carbonate Quiou Sand”. Pre-failureDeformation of Geomaterials. Balkema, Sapporo, 55-61.

Flynn, W. L. (1997). "A Comparative Study of Cyclic Loading Responses and Effects of Cementation on Liquefaction Potential of Calcareous and Silica Sands," M.Sc. Thesis, University of Hawaii, Manoa.

Frydman, S., Hendron, D., Horn, H., and Steinbach, J. (1980). "Liquefaction Study of Cemented Sand.”, Journal of The Geotechnical Engineering Division, ASCE, 106(3), 275-297.

Golightly, C.R., and Hyde, A.F.L. (1988). “Some Fundamental Properties of Carbonates Sands”. Engg. for Calcareous Sediments, Vol. 1, Balkema, 69-78.

Hull, T.S., Poulus, H.G., and Alehossein, H. (1988). “The Static Behavior of Various Calcareous Sediments”. Engg. for Calcareous Sediments, Vol. 1. Balkema, 87-96.

Hyodo, M., Hyde, A. F. L., and Aramaki, N. (1998). "Liquefaction of Crushable Soils.", Geotechnique, 48(4), 527-543.

LoPresti, D. C. F., Pallara, O., Lancellotta, R., and Maniscalco, R. (1993). “Monotonic and Cyclic Loading Behavior of two Sands at Small Strains”. Geotech. Testing J., 16(4),409-424.

Morelock, J., and Ramirez, W. (2004). “Marine Sediments”. <http://geology.uprm.edu/Morelock/GEOLOCN_/sedimt.htm> (February 12, 2006)

Morioka, B. T., and Nicholson, P. G. (2000). "Evaluation of the Liquefaction Potential of CalcareousSand." Proceedings of the Tenth International Offshore and Polar Engineering Conference, Seattle.

Pizzimenti, P.B. (1996) "Stress-Strain Behavior of Surficial Carbonate Sediments from KeyWest, Florida,” MS Thesis, Dept. of Ocean Engrg., URI, 175 p.

Reid, H., and Taber, S., 1919, The Puerto Rico earthquakes of October–November 1918: Bulletin of the Seismological Society of America, 9,95–127.

Tuttle, M.P., Prentice, C.S., Dyer-Williams, K., Pena, L., and Burr, G. (2003),¨Late Holocene liquefaction features in the Dominican Republic: A powerful tool for earthquake hazard assessment¨, BSSA 93(1), 27–46.