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LIQUEFACTION SUSCEPTIBILITY OF A CALCAREOUS SAND FROM SOUTHWEST PUERTO RICO

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ABSTRACT

Calcareous sands are generally composed of skeletal remains of marine organisms and typically have unique mineralogy and particle characteristics such as particle shape, surface roughness, crushability, and intraparticle porosity. Calcareous sands may exist in both cemented and uncemented states. These unique characteristics of calcareous sands suggest that their geotechnical behavior can be different compared to that of terrigenous and silica sands, including their behavior under seismic loading. This paper presents results from an experimental study on the liquefaction susceptibility of an uncemented calcareous sand from southwestern Puerto Rico. The experimental program involved a comprehensive set of undrained cyclic triaxial tests on isotropically consolidated reconstituted samples of this calcareous sand. For comparison purposes, Ottawa silica sand samples at similar conditions were also tested. For this paper, the results are presented in terms of curves of normalized cyclic resistance ratio (CRR) versus number of cycles to liquefaction. The CRR curves were prepared for a range of relative densities and consolidation stresses. Pore pressure generation characteristics are also presented and discussed for both tested sands. In general, test results show that the calcareous sand exhibit higher liquefaction resistance than the Ottawa silica sand tested under similar conditions. The cyclic resistance curves obtained for the calcareous sand from southwest Puerto Rico were found to be higher than similar curves published for calcareous sands of other parts of the world tested under similar conditions.

Keywords: calcareous sands, cyclic resistance, liquefaction resistance

INTRODUCTION

A great portion of the Puerto Rico (PR) coast line is overlain by beach deposits that in many locations consist of uncemented and cemented calcareous sands (Scanlon et al., 1998). Assessment of the liquefaction resistance of calcareous sands from Puerto Rico is of critical importance due to the large area extent of these deposits, widespread coastal and port developments in PR, and the high seismicity of the Caribbean region where PR is located (McCann, 1985). Geotechnical behavior of calcareous sands from PR, particularly under earthquake loading, remains a challenging issue and needs further attention. This study aims to address some of the pressing issues and to fill this important knowledge gap. Specifically, this paper presents a summary of the results from an experimental research carried out with the objective to study the liquefaction resistance of calcareous sands retrieved from surficial beach deposits in Cabo Rojo, southwestern Puerto Rico. The experimental program involved mineralogical and grain

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characterization, critical state line evaluation, and 31 undrained cyclic triaxial tests on isotropically consolidated reconstituted samples of uncemented calcareous sand. The samples were tested at three different relative densities and three isotropic consolidation stress levels. For comparison purposes, the experimental program included similar tests carried out on samples prepared using Ottawa # 20-30 silica sand, which were prepared using similar techniques and were tested at the same relative densities and consolidation stresses.

CABO ROJO CALCAREOUS SANDS

The calcareous sand used in this study was previously documented in the investigations performed by Cataño and Pando (2010). These calcareous sands have grains composed of marine organisms as illustrated in the micrographs shown in Figure 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. These sands have high calcium carbonates contents, with a mineralogical composition that usually includes biogenic grains with calcite and aragonite. 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. Further details pertaining to the tested soils are provided in the experimental program.

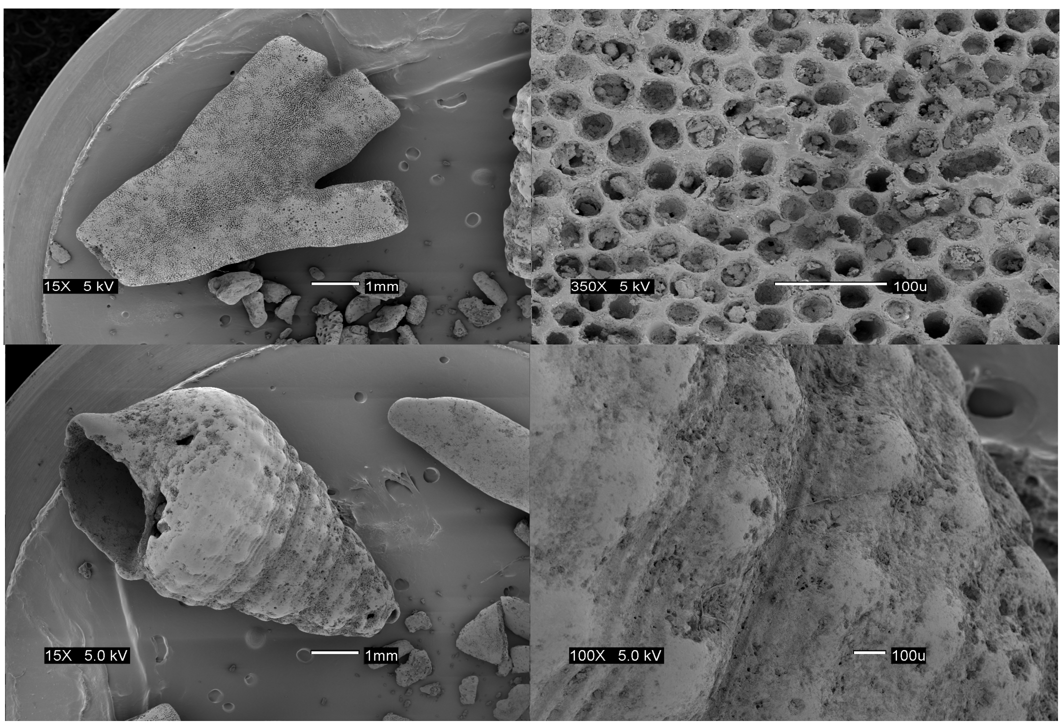

Figure 1. Micrographs for Cabo Rojo calcareous sand (Cataño and Pando, 2010)

PREVIOUS STUDIES ON THE LIQUEFACTION RESISTANCE OF CALCAREOUS SANDS

For background and comparison purposes, Table 1 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%. Typically these studies isotropically consolidated their samples to an effective stress level of 100 kPa. The cyclic resistance curves for these studies are presented in the results and discussions section of this paper.

Table 1. Summary of previous studies on the liquefaction susceptibility of calcareous sands that use 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	
								CSR	Cycles to liquefaction (N_f)
Kurkar (Frydman et al, 1980)	0.10	-	-	59 63	-	-	-	0.20 to 0.40	3
Waikikí A (Flynn and Nicholson, 1997)	0.21	0.14	1.57	65	1.12	1.69	2.79	0.20 to 0.45	34
Waikiki B (Flynn and Nicholson, 1997)	0.74	0.18	5.05	65	0.66	1.303	2.71	0.20 to 0.45	2
Dog Bays (Hyodo et al, 1998)	0.22	0.11	2.36	60	1.61	2.45	2.72	0.21 to 0.40	1
Ewa Plains (Morioka and Nicholson, 2000)	0.82	0.20	4.1	65	0.66	1.30	2.72	0.13 to 0.36	2

EXPERIMENTAL TESTING PROGRAM

The experimental program in this study primarily involved sand mineralogical and grain characterization, critical state line evaluation, and consolidated undrained cyclic triaxial testing of specimens prepared using Cabo Rojo calcareous sand and Ottawa silica sand. A total of 39 consolidated undrained cyclic triaxial tests were performed, of which 31 tests were carried out on Cabo Rojo calcareous sand, and 8 were carried out on Ottawa silica sand Table 2 summarizes the principal parameters and results of these 39 tests.

Description of sand materials used

The calcareous sand studied was retrieved from Cabo Rojo, southwestern Puerto Rico, and was the same sand studied by Cataño and Pando (2010). This sand is fine to medium grained, poorly graded, and white to yellow in color, with sub-angular to angular grains, with high internal porosity. The grain characteristics were shown in Figure 1. The calcium carbonate of this sand was measured to be at least 91%. The main index properties of this sand are listed in Table 3. The index properties of the Ottawa sand used for comparison purposes are also listed in this table. The grain size distributions of both test sands are shown in Figure 2. 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.

Critical state line for the Cabo Rojo calcareous sand

The critical state line for Cabo Rojo calcareous sand is shown in Figure 3. This critical state line was defined using CU triaxial test data from Cataño and Pando (2010) and complemented with data (see open symbols) obtained for this research using the method proposed by Santamarina and Cho (2001).

Table 2. Test matrix of cyclic triaxial tests

Sand Name	σ'_{3cons} (kPa)	Test Number	$D_{rend\ cons}$ (%)	$e_{end.cons}$	CSR	Cycles to liquefaction (N_f)
Cabo Rojo calcareous sand	50	A.5.1	29.1	1.906	0.238	104
		A.5.2	28.3	1.910	0.260	4
		A.5.3	26.7	1.920	0.245	123
		A.5.4	26.0	1.924	0.260	10
		A.5.5	26.1	1.923	0.2725	5
Cabo Rojo calcareous sand	100	A.5.6	25.7	1.925	0.155	20
		A.5.7	26.7	1.920	0.180	13
		A.5.8	31.9	1.891	0.195	10
		A.5.9	28.5	1.909	0.220	5
		A.5.10	47.1	1.807	0.160	122
		A.5.11	44.9	1.819	0.1925	20
		A.5.12	44.5	1.821	0.205	15
		A.5.13	45.9	1.813	0.240	7
		A.5.14	44.0	1.823	0.250	8
		A.5.15	64.4	1.711	0.225	536
		A.5.16	63.5	1.716	0.250	153
		A.5.17	64.5	1.710	0.350	20
		A.5.18	62.2	1.723	0.415	10
		A.5.19	81.3	1.617	0.300	507
		A.5.20	79.4	1.627	0.325	327
		A.5.21	78.5	1.633	0.440	35
Cabo Rojo calcareous sand	200	A.5.22	50.1	1.79	0.065	5846
		A.5.23	49.5	1.793	0.125	56
		A.5.24	50.7	1.787	0.175	23
		A.5.25	64.4	1.711	0.150	123
		A.5.26	64.7	1.709	0.190	72
		A.5.27	64.9	1.708	0.225	21
		A.5.28	65.4	1.705	0.300	17
		A.5.29	82.0	1.613	0.220	345
		A.5.30	82.8	1.609	0.300	30
		A.5.31	80.0	1.624	0.350	12
Ottawa silica sand	50	A.5.32	25.6	0.070	0.070	142
		A.5.33	25.6	0.088	0.0875	31
		A.5.34	23.4	0.10	0.100	23
		A.5.35	24.5	0.125	0.125	6
Ottawa silica sand	100	A.5.36	66.8	0.125	0.125	1042
		A.5.37	66.8	0.200	0.200	52
		A.5.38	70.0	0.250	0.250	7
		A.5.39	69.5	0.270	0.270	4

Cyclic triaxial testing procedure

The liquefaction resistance for both sands tested was evaluated by means of consolidated undrained cyclic triaxial tests carried out in accordance with the procedure described in ASTM-D5311. Cyclic triaxial tests were performed using a Geocomp cyclic triaxial device that is composed of a LoadTracII system and two FlowTracII units.

Table 3. Summary of index properties for the two tested sands

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	Alternative Method
e_{min}	1.51	0.50	

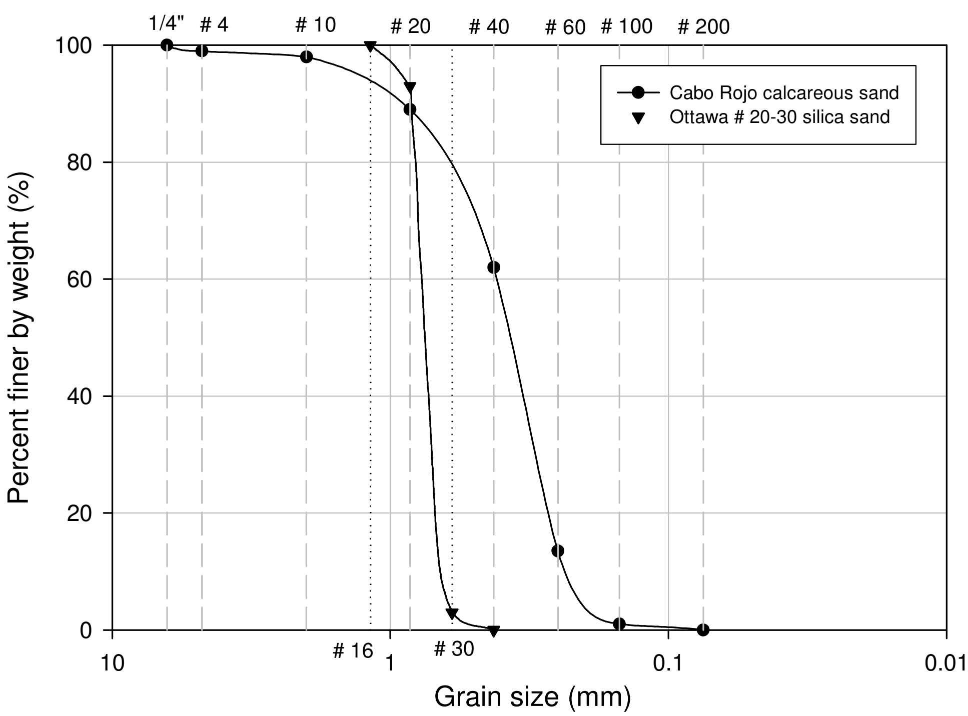

Figure 2. Grain size distribution for the two tested sands

Cyclic triaxial test specimens were prepared using the "moist tamping" technique using five layers and the under-compaction method suggested by Ladd (1976). Prepared samples were approximately 102 mm high and with a 51 mm diameter. The moist tamping was carried out using moisture contents between 4% and 25% for the Cabo Rojo calcareous sand, and between 2% and 8% for the Ottawa silica sand. The lower moisture content values were used to produce very loose specimens, while the higher moisture content values were used to prepare the denser samples. 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 from bottom to top with carbon dioxide (CO_2) at a pressure near to 15 kPa for 30 to 45 minutes. After CO_2 flushing, samples were 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. This procedure was carried out until B-values greater than 0.95 were achieved.

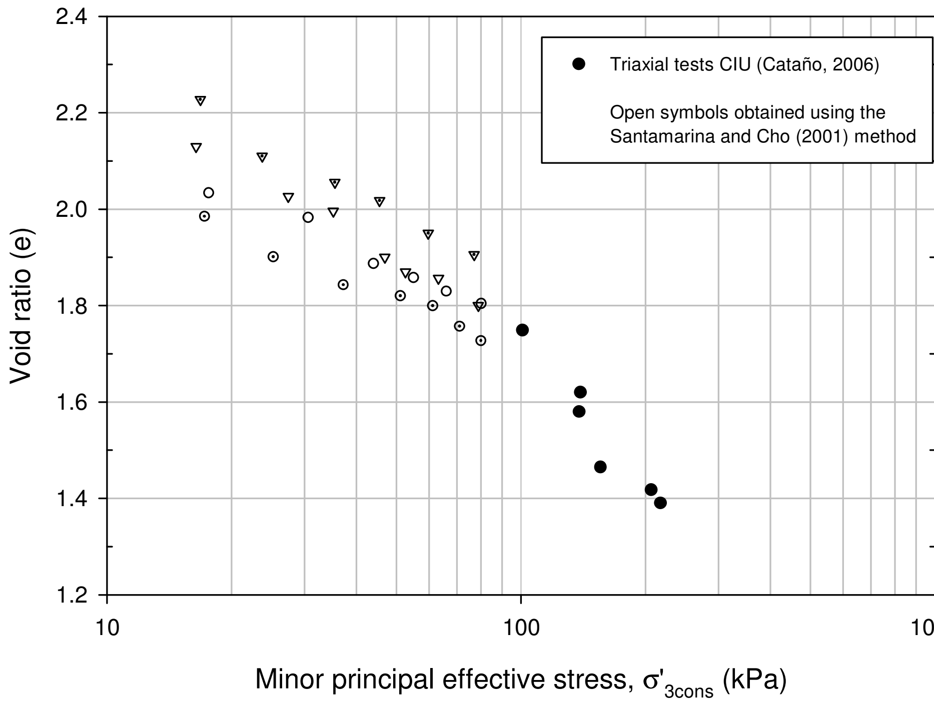

Figure 3. Critical state line for Cabo Rojo calcareous sand

Once sample saturation was ensured, specimens were isotropically consolidated under three different effective stress levels (50, 100, and 200 kPa). When the consolidation stress was reached, specimens were allowed to stabilize under this stress for at least 30 minutes, and the cyclic loading phase was initiated. The isotropically consolidated samples were subjected to stress-controlled cyclic triaxial tests at a frequency of 1 Hz.

RESULTS AND DISCUSSIONS

In this study, the number of load cycles to liquefaction in response to the applied Cyclic Stress Ratio (CSR), were investigated. For cyclic triaxial tests, the cyclic stress ratio is defined as the ratio between the maximum applied cyclic shear stress and the effective consolidation stress (σ'_{3cons}), as follows:

$$CSR = \sigma_d / 2\sigma'_{3cons} \quad (1)$$

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 4. For comparison purposes, Figure 5 shows select CSR curves obtained with Ottawa silica sand samples.

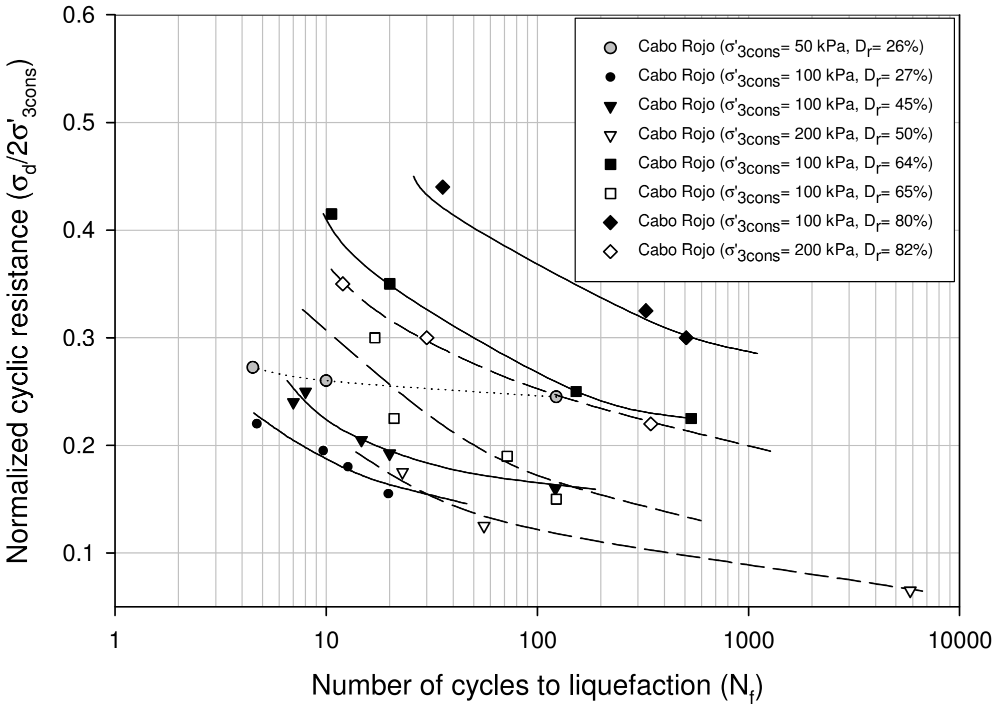

Figure 4. Cyclic resistance curves for Cabo Rojo calcareous sand

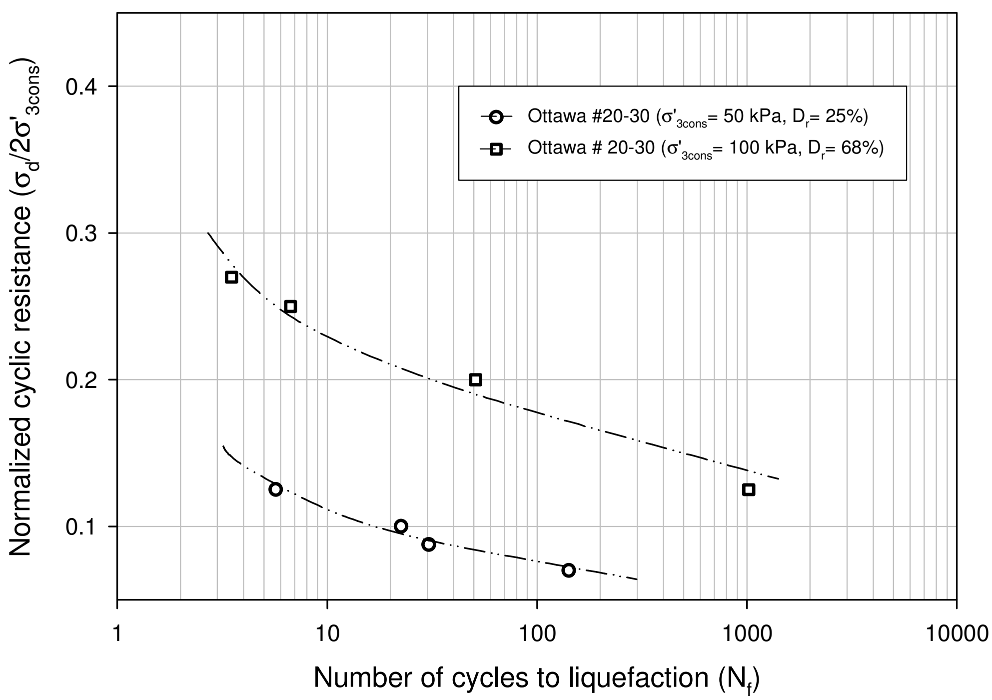

Figure 5. Cyclic resistance curves for Ottawa silica sand

Influence of relative density in liquefaction resistance

Liquefaction resistance was found to increase with increasing relative density, as is illustrated in Figure 6, 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.

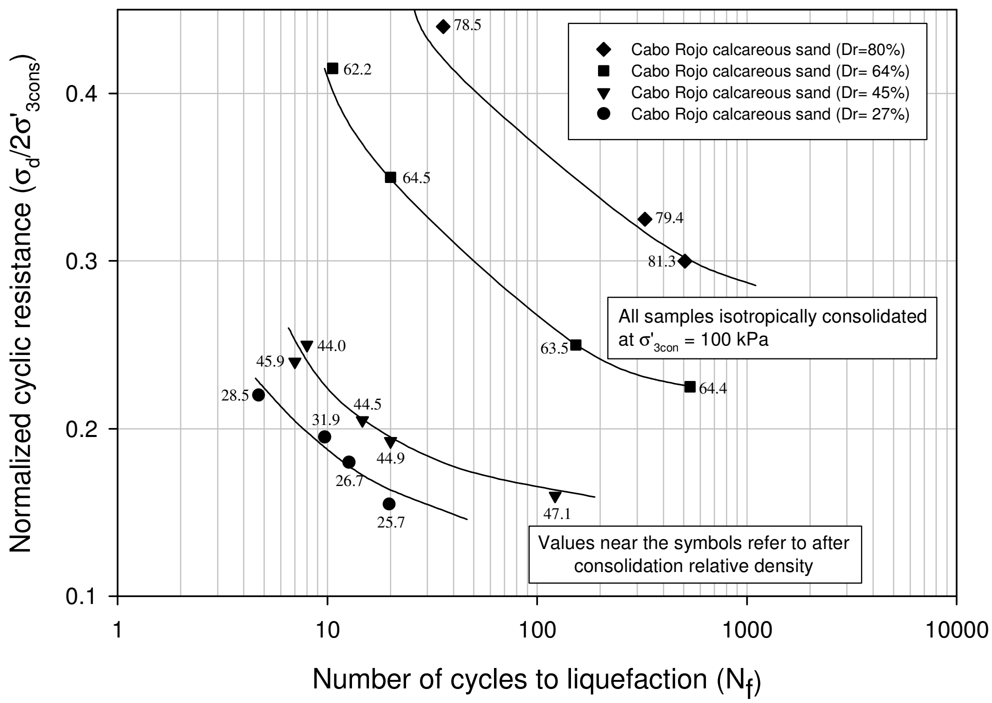

Figure 6. Cyclic resistance curves for Cabo Rojo sand at similar consolidation stress

Influence of consolidation effective stress in liquefaction resistance

Figure 7 shows CRR curves for the Cabo Rojo calcareous sand tested at a medium dense state (Dr ≅ 64 – 65%), and consolidated under effective stresses of 100 and 200 kPa. It can be seen that for these sets of samples, the liquefaction resistance decreases with increasing consolidation stress for this particular value of medium dense relative density.

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 8 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 9 for samples prepared at a medium dense state (D_R : 64 – 68%), and consolidated to 100 kPa. From these two 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.

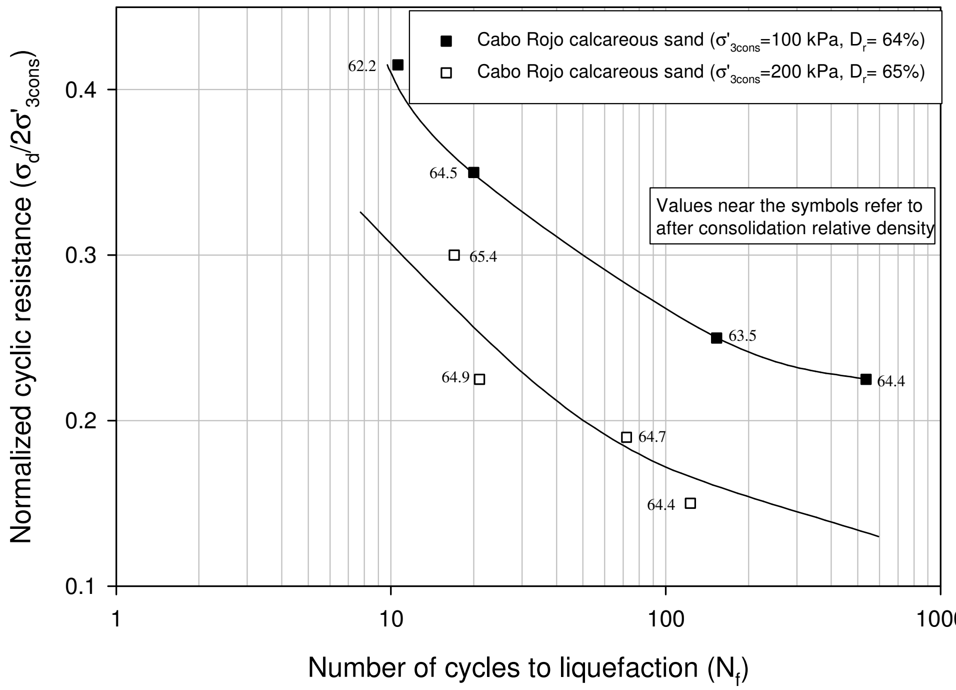

Figure 7. Cyclic resistance curves for Cabo Rojo calcareous sand at similar relative density

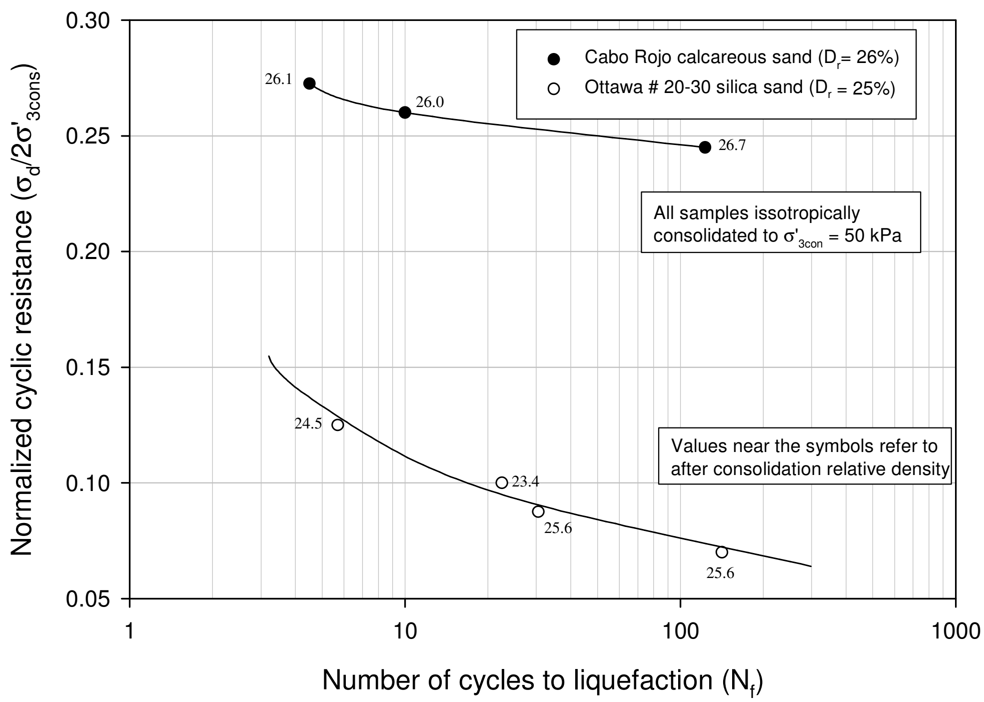

Figure 8. Cyclic resistance curves for the Cabo Rojo and Ottawa sands at loose relative density

Excess Pore pressure generation

The excess pore pressures generated during the undrained cyclic loading phase of the triaxial test are summarized in Figure 10 which shows the pore pressure generation curves for medium to dense state (D_R= 64 – 68%), for both Cabo Rojo and Ottawa sands consolidated to 100 kPa.

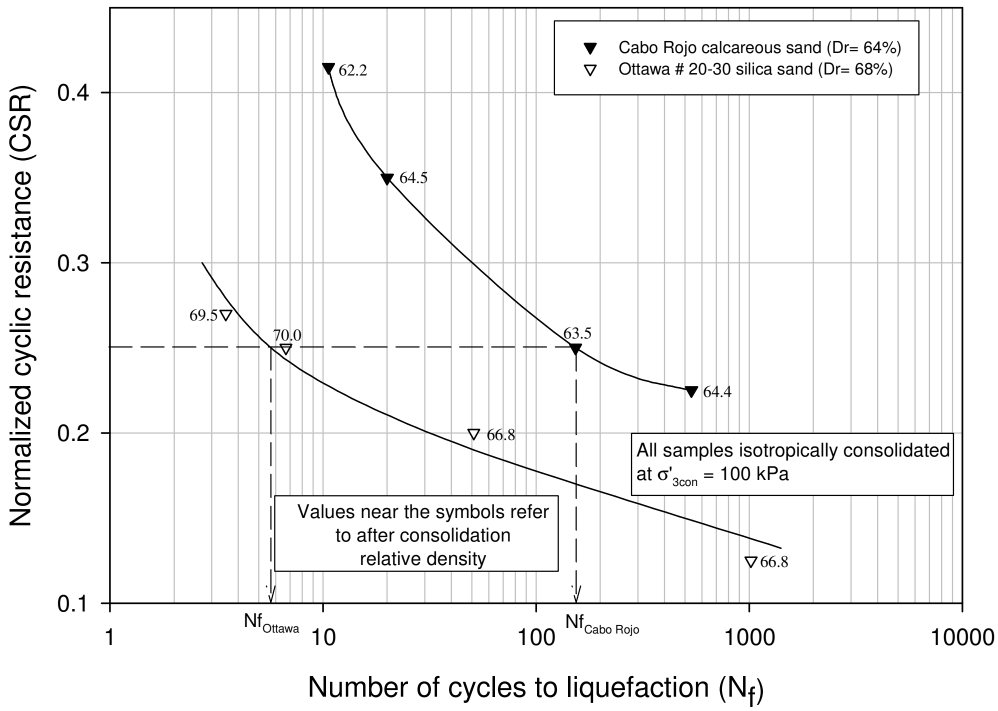

Figure 9. Cyclic resistance curves for Cabo Rojo and Ottawa sands at medium relative density

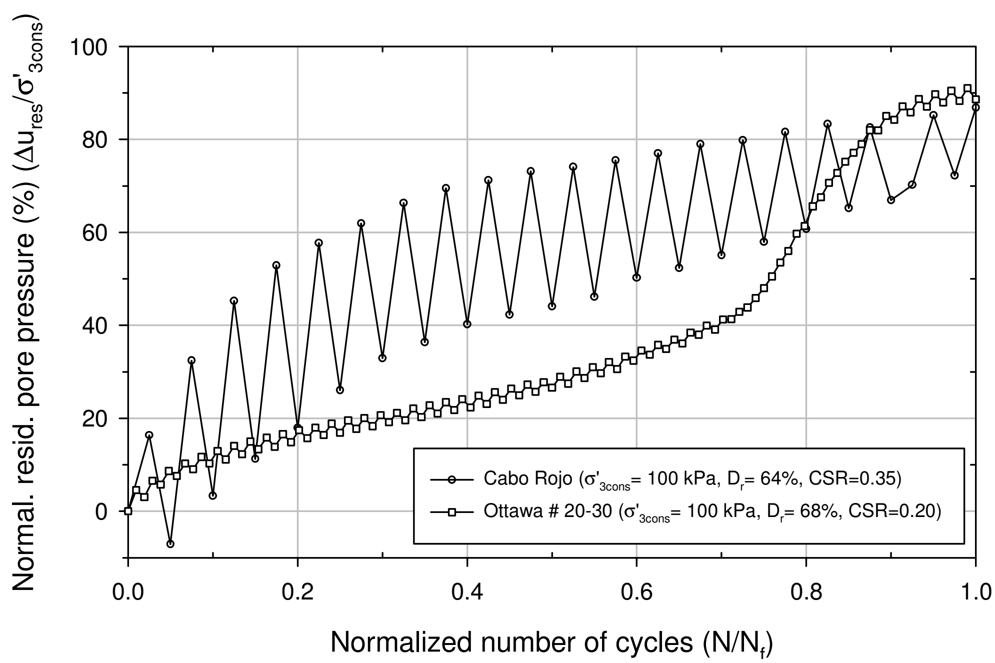

Figure 10. Excess pore pressure generation curves for Medium to Dense Cabo Rojo and Ottawa sands isotropically consolidated to an effective stress of 100 kPa

In Figure 10, residual excess pore pressures (Δu_{res}) normalized with respect to the consolidation stress (σ'_{3con}) are presented as a function of normalized number of cycles to reach liquefaction (i.e., N/N_f). Residual excess pore pressure (Δu_{res}) is defined as the excess pore pressure value when the applied deviator stress is zero during each load cycle (Seed and Lee, 1966).

From Figure 10 it is possible to distinguish the important differences in excess pore pressure generation characteristics between the Cabo Rojo calcareous sand and the Ottawa silica sand. Cabo Rojo sand develops larger excess pore pressures than the Ottawa sand during the earlier stages of the cyclic loading phase. Also between loading cycles, the calcareous sands exhibited larger fluctuations in the excess pore pressure, suggesting some sort of stress relaxation between loading cycles. The Ottawa silica sand, on the other hand, showed a slow and gradual generation of excess pore pressures during the initial phase of the cyclic loading of the test and very small fluctuations of pore pressures between cycles. Another important difference is that towards the end of the tests, i.e., as the sample approached liquefaction, the Ottawa sands typically showed a sudden or abrupt increase in the excess pore pressures, while the Cabo Rojo sands showed a more gradual or incremental increase of the pore pressures as it reached liquefaction.

The large fluctuations in the excess pore pressures exhibited by the calcareous sands during loading cycles could be due to particle rearrangement due to the characteristics of the contact areas between grains, which include unique particle shapes, surface roughness, intra-grain porosity, etc. The occurrence of large pore pressure relaxations between loading cycles could contribute towards the greater cyclic resistance exhibited by the Cabo Rojo calcareous sands compared to the Ottawa silica sand. The excess pore pressure generation characteristics of the Cabo Rojo sand was found to be similar to the one reported by Morioka and Nicholson (2000) and Ross and Nicholson (2000) for two calcareous sands from Hawaii.

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

As mentioned earlier, and summarized in Table 1, there are several studies on the liquefaction resistance of calcareous sands from other regions of the world. Figure 11 compares the CRR curves obtained from this study for the Cabo Rojo calcareous sand with results reported for other calcareous sands tested under similar conditions (in this case, a medium dense state D_R : 59 – 65%, and isotropically consolidated to an effective stress of 100 kPa). It can be seen from Figure 11, that the Cabo Rojo calcareous sands exhibited higher liquefaction resistance than other calcareous sands tested in previous studies tested under similar conditions and test procedures.

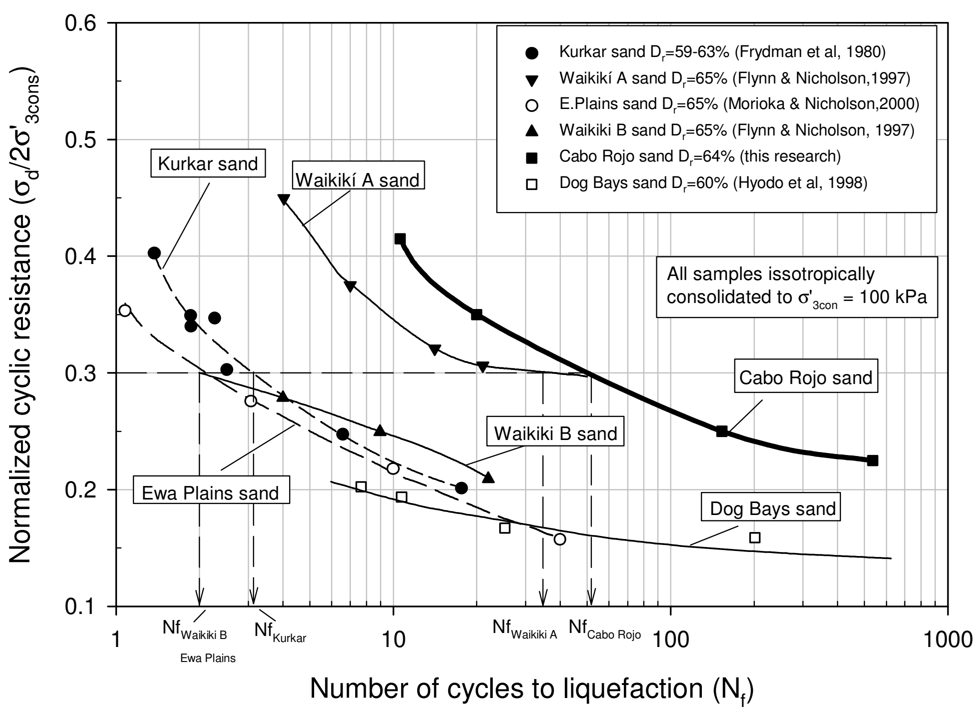

Figure 11. Comparison of cyclic resistance curves for Cabo Rojo and other calcareous sands

CONCLUSIONS

This paper presents a summary of the experimental study carried out to assess the liquefaction resistance of an uncemented calcareous sand from Cabo Rojo, Southwestern Puerto Rico. The cyclic triaxial tests revealed important differences between the response of the Cabo Rojo calcareous sand and samples prepared with Ottawa silica sand tested under similar conditions. The results showed that the 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 Cabo Rojo calcareous sands also exhibited unique characteristics in their pore pressure generation curves, showing large fluctuations between loading cycles. These fluctuations could be attributed to stress relaxations due to the unique characteristics of this sand, such as particle shape, roughness, intra-particle porosity which will result in important differences in the characteristics and intensity of particle contacts in the samples of these sands compared to Ottawa silica sand samples.

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REFERENCES

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.

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.

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,

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

Ladd, R. S. (1976). "Preparing Test Specimens Using Undercompaction." Geotechnical Testing Journal, GTJODJ, 1(1), 16-23.

McCann, W.R. (1985). "On the earthquake hazards of Puerto Rico and the Virgin Islands", Bulletin of the Seismological Society of America, 75(1), 251-262.

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

Ross, M. S., and Nicholson, P. G. (1995). "Liquefaction Potential and Cyclic Loading Response of Calcareous Soils." Research Report UHM/CE/95-05, University of Hawaii, Manoa, Hawaii.

Santamarina, J. C., and Cho, G. C. (2001). "Determination of Critical State Parameters in Sandy Soils - Simple Procedure " ASTM Testing Journal, 24(2), 185-192.

Scanlon, K.M., Rodríguez, R.W., Trias, J. L., and Delorey, C.M. (1998). "Offshore sediments and Sand and Gravel Resources on the Insular Shelf of Puerto Rico." USGS Open-File Report 98-38.

Seed, H. B., and Lee, K. L. (1966). "Liquefaction of Saturated Sands During Cyclic Loading." J. of the Soil Mechanics and Foundation Division, ASCE, 92(3), 25-58.