

## Evaluation of the Cyclic Resistance of an Uncemented Calcareous Sand Deposit from Puerto Rico Using Shear Wave Velocity

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### ABSTRACT

This paper presents the results of a laboratory study on the cyclic resistance of a loose, uncemented, calcareous sand deposit from Puerto Rico. A soil-specific relationship between cyclic resistance (CRR) and shear wave velocity ( $V_{s1}$ ) was developed from a series of  $K_o$ -consolidated, constant volume cyclic simple shear tests with bender elements. Values of shear wave velocity were high, with  $V_{s1}$  values ranging from 220 to 270 m/s over a range of relative densities. Despite the high values of shear wave velocity, values of cyclic resistance were low, and the resulting CRR- $V_{s1}$  curve was “flatter” than the field-based curves proposed by Andrus and Stokoe (2001) and Kayen et al. (2013). Particle crushing was ruled out as a possible cause as grain size analyses before and after testing showed no evidence of this. With the lack of sensitivity between CRR and  $V_{s1}$  and the known problems of particle crushing associated with Standard Penetration and Cone Penetration tests, there are still significant challenges in assessing the liquefaction potential of calcareous soils.

### Introduction

Calcareous sands pose many geotechnical challenges compared to silica sands due to their brittleness and potential for cementation. These challenges include accurate determination of the capacity of deep foundations (Datta et al. 1982; Nauroy and LeTirant 1985), the effectiveness of ground improvement (Al-Homoud and Wehr 2006), and liquefaction during cyclic loading (e.g. Frydman et al. 1980; Ross and Nicholson 1995; Flynn 1997; Morioka and Nicholson 2000; and Pando et al. 2012, among others). Liquefaction of calcareous sands occurred during earthquakes in Guam (1993), Hawaii (2006), and Haiti (2010). In each of these cases, liquefaction of calcareous sands resulted in extensive damage to homes, hospitals, schools, government and port facilities, and offshore structures. Figure 1 illustrates liquefaction features such as ground cracks, lateral spreading and sand boils in calcareous sands during the Hawaii 2006 and Haiti 2010 earthquakes.

The objective of this paper is to present the results of a series of  $K_o$ -consolidated, constant volume cyclic direct simple shear tests (CDSS) with shear wave velocity measurements carried out on two different sands: (1) a silica-based sand called Monterey 0/30 and (2) an uncemented, calcareous sand from southwestern Puerto Rico, USA (PR) called Cabo Rojo sand. The results of the laboratory testing program were used to develop soil-specific cyclic resistance-shear wave velocity relationships for both soils so that a comparison of the behavior of a carbonate and silica sand could be made. Shear wave velocity was used because it is strongly influenced by the behavior of particle contacts and there is increasing evidence that the relationship between cyclic

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resistance and shear wave velocity is soil-specific (Tokimatsu et al. 1986, Baxter et al. 2008).



Figure 1. (a) Ground cracks resulting from lateral spreading and liquefied sand ejected from ground cracks, Hawaii 2006  $M_w=6.7$  earthquake (adapted from Medley, 2006) and (b) post-earthquake satellite/aerial imagery of the port at Puerto Principe, Haiti 2010  $M_w=7.0$  earthquake showing extensive damage and sand ejecta (Rathje et al. 2010).

### Properties of the Monterey and Cabo Rojo Sand

The silica sand selected for this study (Monterey 0/30) was chosen because of its extensive use in laboratory liquefaction studies in the literature (e.g., Silver 1976, Mulilis 1977, De Alba et al. 1984). The calcareous sand was collected from a beach in Cabo Rojo, Puerto Rico, USA and was tested previously by Pando et al. (2012) and Doblting (2013). According to the Unified Soil Classification System (ASTM D 2488-00) both soils classify as poorly graded sands (SP). Table 1 presents a summary of the main index properties obtained from the soil characterization testing.

Table 1. Index properties of the soils selected for this study.

Parameter		Monterey Sand	Cabo Rojo Sand	ASTM Standard
$D_{10}$	mm	0.33	0.24	ASTM D 422-63
$D_{30}$	mm	0.45	0.3	
$D_{50}$	mm	0.55	0.37	
$D_{60}$	mm	0.58	0.42	
$C_u$		1.76	1.75	
$C_c$		1.06	0.89	
$G_s$		2.66	2.87	ASTM D 854-06
$\gamma_{dmin}$	$kN/m^3$	14.4	10.2	ASTM D 4254-00
$e_{max}$		0.808	1.75	
$\gamma_{dmax}$	$kN/m^3$	16.4	12	ASTM D 4253-00
$e_{min}$		0.589	1.34	

The Cabo Rojo sand had a high value of specific gravity (2.87) and very high maximum and minimum void ratios ( $>1.0$ ) compared to the Monterey sand. Very high void ratios, high values of specific gravity, a wide variety of particle sizes and shapes, higher grain crushability, brittle stress-strain behavior, and higher compressibility are some of the unusual yet typical

characteristics of calcareous sands. Mineralogical studies on the Cabo Rojo sand (X-Ray Diffraction and bulk carbonate content) indicated a predominance of calcite and aragonite and carbonate contents greater than 95%.

### **Cyclic Resistance of the Monterey and Cabo Rojo Sand**

The cyclic resistance of the Cabo Rojo and Monterey sand was assessed by means of  $K_o$ -consolidated constant volume cyclic direct simple shear tests with shear wave velocity measurements. A fully automated cyclic DSS manufactured by the GeoComp Corp.® was used to perform these tests. Teflon-coated stacked rings were used to provide lateral confinement of the samples. The samples were sheared under constant volume conditions rather than truly undrained conditions, meaning that the height of the sample is kept constant during the shear phase and there is no direct measurement of the excess pore water pressure. In fact, in this study the soil samples were not saturated and were prepared as either dry or moist samples ( $S=55\%$ ). In a constant volume direct simple shear test, it is assumed that the change in applied vertical stress as the specimen height is maintained constant during shear is equal to the excess pore pressure which would have been measured in a truly undrained test with constant total vertical stress (Bjerrum and Landva 1966). This assumption has been verified for monotonic simple shear tests on saturated clays (Vucetic and Lacasse, 1983 and Dyvik et al. 1987). To the authors' knowledge, however, this has not been verified for cyclic simple shear tests on sands. For this study, samples were prepared using two different methods: dry pluviation (DP) and modified moist tamping (MMT) in which the molding water content corresponded to a degree of saturation of 55%. Sample dimensions were 63.5 mm in diameter and approximately 25.4 mm in height. This diameter measurement included the correction for the membrane thickness used to contain the sample. Special care was taken when preparing the moist samples because of the possibility of developing capillary stresses but this phenomenon was ruled out because the trend between the dry and moist samples was the same. All samples were subjected to a vertical effective consolidation stress of 100 kPa, which corresponds to a mean effective stress of 57 kPa assuming a value of  $K_o$  equal to 0.36 (based on a measured value of  $\phi' = 40^\circ$ ). Samples were sheared under constant volume conditions and subjected to a sinusoidal cyclic load at a frequency of 0.5 Hz. Liquefaction was defined at a double amplitude strain of 3.75%. Shear wave velocity was measured at the end of consolidation and was determined in the time domain by identifying the "first deflection" of the shear wave (Lee and Santamarina 2005). A single sine wave with an amplitude of 20 Volts peak-to-peak and frequency of 20 kHz was used to generate the shear wave. Shear waves were calculated using the tip-to-tip distance (corrected for change in height during consolidation) from the top of the bottom bender to the bottom of the top bender element. For this study two different waveforms were evaluated for estimating the shear wave velocity: (1) sinusoidal wave and (2) square wave, both at an amplitude of 20 Volts peak to peak, as illustrated in Figure 2.

A range of frequencies were evaluated for the sinusoidal input signal in addition to the square wave. Given the short height of the CDSS specimens (<25 mm), frequency ranges that would give clear received signals with little or no near field effect were in the range of 15-25 kHz for the sinusoidal wave. Frequencies were selected by trial-and-error and from experience with taller samples (i.e. triaxial specimens). Based on the amplitude and clarity of the received signals, a single sine wave at a frequency of 20 kHz was used for this study.

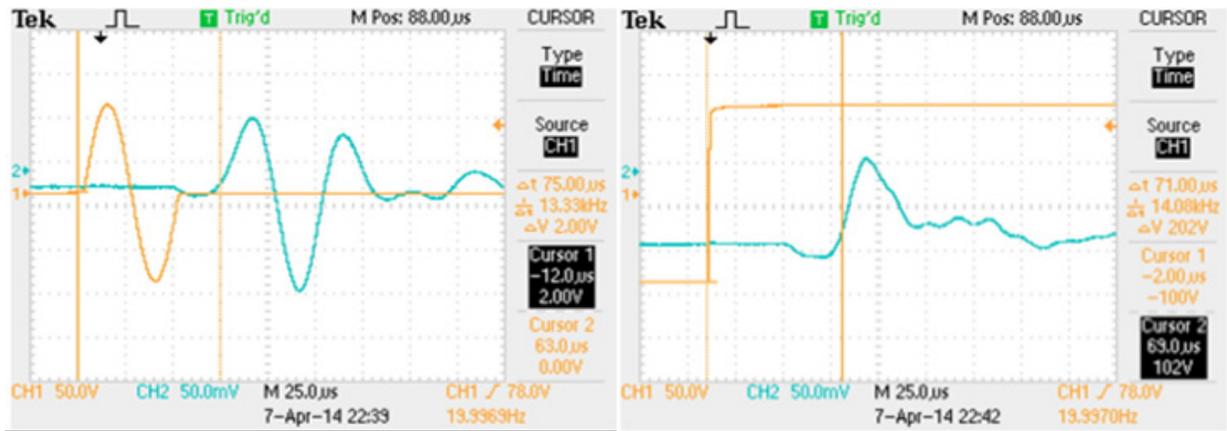
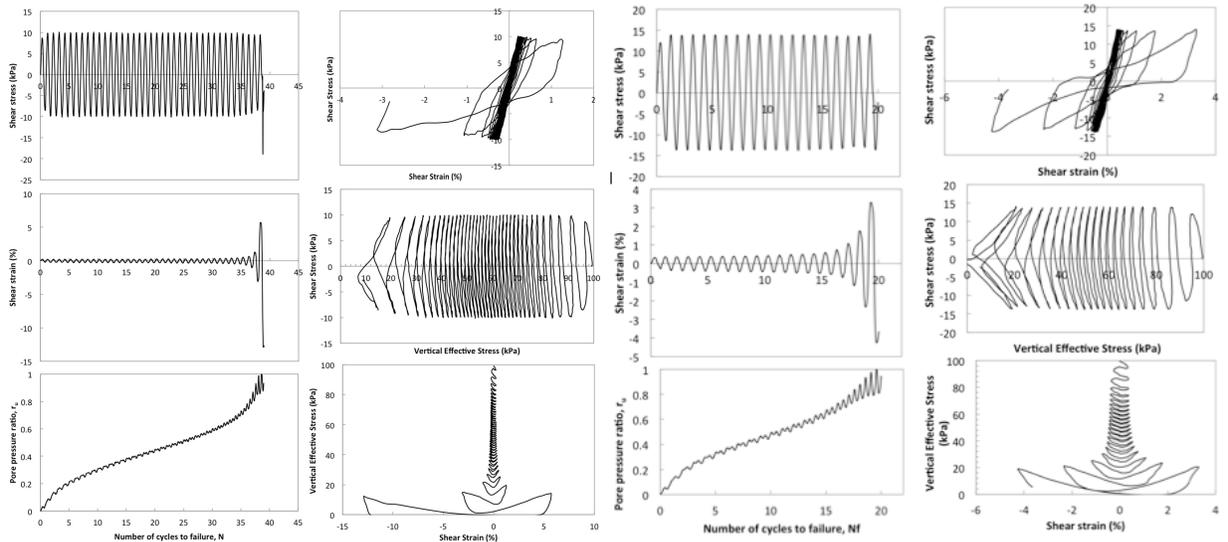


Figure 2. Illustration of the two waveforms (sinusoidal wave versus rectangular wave) used for this investigation (25.4 mm in height dry pluviated Cabo Rojo sand sample,  $\sigma'_v=100$  kPa).

The results of a single test for a loose and dense sample of Cabo Rojo sand are shown in Figure 3. The figures on the left show the applied stress, shear strain and pore pressure ratio versus the number of cycles of loading. The figures on the right show the stress-strain behavior, the reduction in vertical stress in  $\sigma'-\tau$  space, and the reduction in vertical effective stress versus shear strain. For these particular tests, the samples reached failure after 38 and 19 cycles of loading, respectively. The cyclic resistance ratio (CSR) was defined as the ratio of the cyclic shear stress to the effective vertical consolidation stress. The reported void ratios ( $e_c$ ) correspond to the final void ratios, after the consolidation phase was completed.



(a) CSR=0.099,  $e_c=1.58$ ,  $\sigma'_{vo}=100$  kPa,  $D_r=41.5\%$     (b) CSR=0.138,  $e_c=1.38$ ,  $\sigma'_{vo}=100$  kPa,  $D_r=90.2\%$

Figure 3. Typical CDSS test results on loose and dense Cabo Rojo sand prepared by dry pluviation.

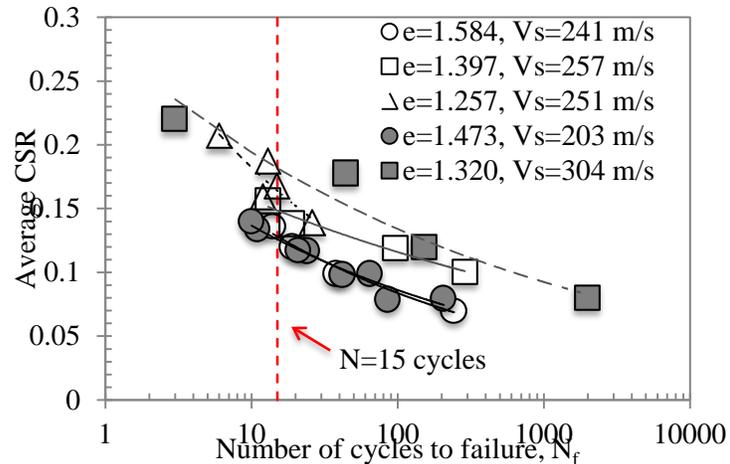


Figure 4. Cyclic resistance of the Cabo Rojo sand obtained by dry pluviation (open circles) and modified moist tamping (closed circles).

Figure 4 is a combined plot of cyclic resistance with samples prepared by both dry pluviation and moist tamping. A dashed line is drawn at  $N_f = 15$  cycles, which has been used to represent the cyclic resistance corresponding to a magnitude 7.5 earthquake (Seed and Idriss 1971). Studies from the literature (e.g., Mulilis et al. 1977) have shown that different sample preparation methods results in different cyclic resistances, and it is generally understood that moist tamping produces stiffer samples than other sample preparation methods (i.e., dry pluviation, slurry deposition). This was not seen for the Cabo Rojo sand. In fact, there is not a consistent trend of increasing shear wave velocity and cyclic resistance. One possible explanation for this is that the range of cyclic resistances is quite low (approximately 0.13 to 0.18 at 15 cycles of loading) over a wide range of relative densities and shear wave velocities.

Figure 5 shows the results for all the cyclic direct simple shear tests performed on the Monterey sand. This figure shows no clear trend between either density or shear wave velocity and the cyclic resistance. This is not reasonable, however no clear explanation for these results could be found. There is a slight trend between shear wave velocity and cyclic resistance. Tests on the loose dry pluviated specimen ( $e = 0.717$ ,  $D_r = 41.6\%$ ) yielded the lowest shear wave velocities, equal to 257 m/s. The shear wave velocities obtained for both dense specimens,  $e = 0.61$  ( $D_r = 90.4\%$ ) and  $e = 0.559$  ( $D_r = 113.7\%$ ), were very similar and in the order of 287 m/s and 281 m/s. Given that there is almost no difference in the cyclic strength for the dense specimens, the fact that the shear wave velocities are very similar is reasonable. Identical trends were observed for the tests performed on moist tamped specimens.

Figure 6 shows the  $CRR-V_s$  data at  $N_f = 15$  for the Cabo Rojo and Monterey sand prepared using the dry pluviation and the modified moist tamping techniques. This figure also includes results of a study by Brandes (2011) carried out on a calcareous sand from Hawaii called Kawaihae sand and a standard silica sand called Nevada sand. These sands were also tested under constant volume CDSS conditions, prepared using the dry pluviation method, and shear wave velocities were measured at the end of the consolidation phase. The CDSS apparatus was manufactured by the Norwegian Geotechnical Institute and the samples were confined laterally using a wire-reinforced membrane.

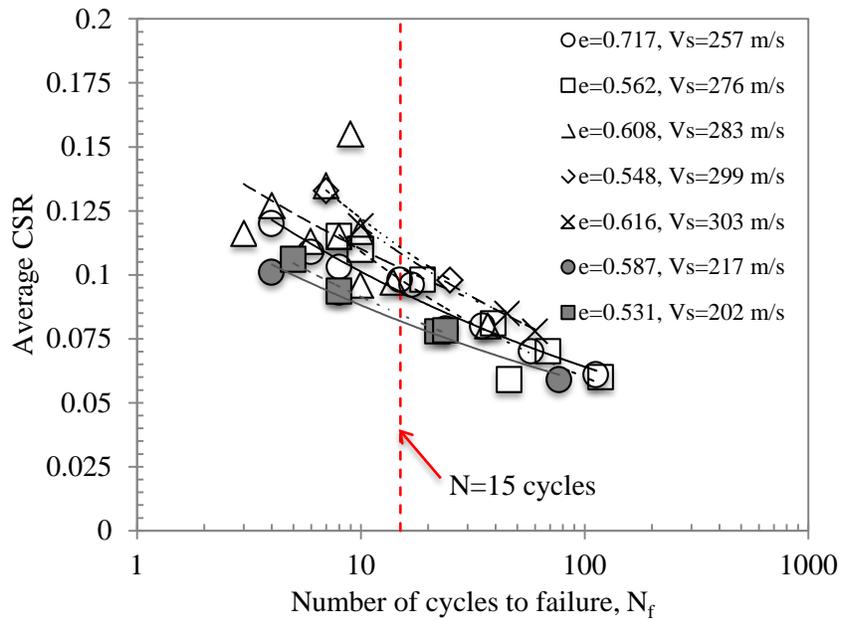


Figure 5. Cyclic resistance obtained of the Monterey sand obtained by dry pluviation (open circles) and modified moist tamping (closed circles).

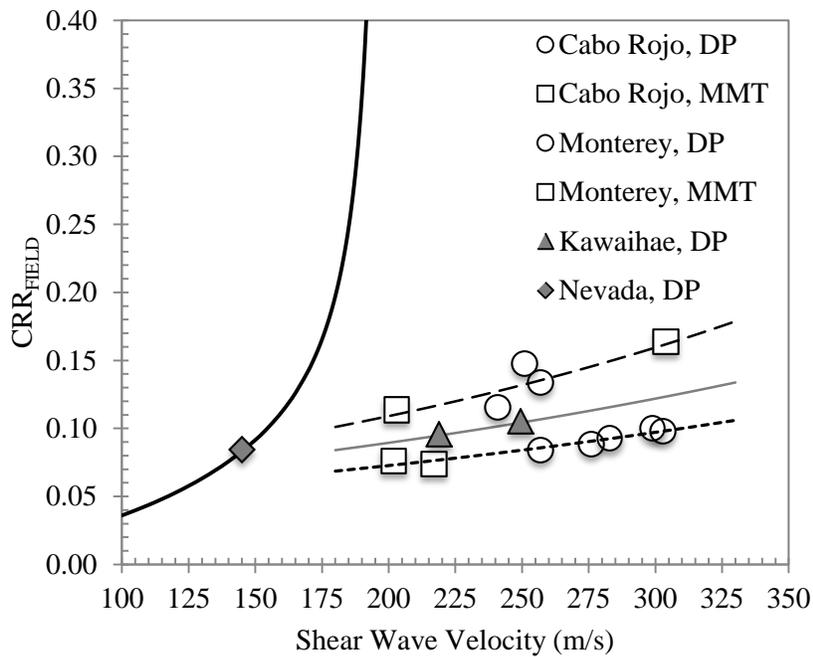


Figure 6.  $CRR-V_s$  relationship for samples of Cabo Rojo sand and Monterey sand prepared using the dry pluviation and modified moist tamping technique and results obtained by Brandes (2011) on Hawaiian sands against the field-based approach developed by Andrus and Stokoe (1997).

## **CRR- $V_s$ Relationships and Discussion of Results**

The results support the hypothesis that the CRR- $V_s$  relationship is independent of sample preparation methods and also appears to be soil-specific. This is consistent with the findings reported by Tokimatsu et al. (1986) on Niigata sand and Baxter et al. (2008) on non-plastic silts. One striking difference between the results of this study and other published CRR- $V_s$  relationships is the insensitivity of the cyclic resistance to a wide range of shear wave velocities (i.e. the flatness of the curves). Another manifestation of the flatness of the CSR- $V_s$  relationship for the three soils shown in Figure 5 is the lack of significant dilation in the denser (higher  $V_s$ ) samples during shear. Some dilation can be observed, such as the “banana shaped” stress-strain loops in Figure 2(b), but it is clearly not enough to mobilize significant cyclic resistance. Particle crushing was ruled out as a possible cause as grain size analyses before and after testing showed no evidence of this. It is not clear why more cyclic resistance was not mobilized for the high shear wave velocity samples or whether this is unique to the two simple shear devices from where this data was obtained.

It is also striking that the values of shear wave velocity measured in this study are significantly higher than reported in other studies. These values of shear wave velocity were found to be consistent over a range of input signal frequencies and are believed to be due to the high frictional behavior of the calcareous particles. Possible influences of suction on the velocities of the moist tamped samples were discounted because of the general consistency with the results from the dry pluviated samples. Finally, the CRR- $V_s$  relationships developed in this study are consistent with published results of a calcareous sand in Hawaii (Brandes 2011).

## **Summary and Conclusions**

The objective of the laboratory program designed for this study was to develop the CRR- $V_s$  relationship for the Cabo Rojo sands collected at the study site in PR, as well as the standard silica based Monterey 0/30 sand for use in evaluating field-based liquefaction approaches. A series of  $K_o$ -consolidated constant volume CDSS tests with shear wave velocity measurements were performed on the two sands. Tests for each sand were carried out on samples prepared to loose and dense states. To evaluate the effects of soil fabric on the cyclic resistance of soils, samples were prepared using two different sample preparation methods: dry pluviation and modified moist tamping.

The curves obtained for the Cabo Rojo and Monterey sand are to the right of the field-based curve and the values of cyclic resistance exhibit striking insensitivity to shear wave velocity. This behavior suggests (1) the CRR- $V_s$  relationship is soil specific, (2) the use of field-based curves available in the literature may not be appropriate for all soils. It also suggests that the CRR- $V_s$  relationships under simple shear conditions may be significantly different than those determined from cyclic triaxial tests. Similar behavior was observed from test results for a calcareous and silica sand obtained from the literature.

## **Acknowledgements**

This research was funded jointly by grants from the University of Rhode Island Transportation Center (URITC), the Rhode Island Department of Transportation, and the National Science Foundation (CMMI

Grant No.1234780). This support is greatly appreciated. Special thanks to Mr. Alan Crumley from GeoConsult for his assistant during the geotechnical site investigation.

## References

- Al-Homoud, A.S., and Wehr, W. Experience of Vibrocompaction in Calcareous Sand of UAE. *Geotechnical and Geological Engineering* 2006; **24** (3): 757-774.
- Andrus, R.D. and Stokoe, K.H. II. Liquefaction Resistance Based on Shear Wave Velocity, *NCEER Workshop 011 Evaluation of Liquefaction Resistance of Soils*, Technical Report NCEER-97-0022 1997; T. Youd and I. M. Idriss. Eds. 4-5 Jan. 1996. at Ctr. for Earthquake Engrg. Res Butfalo, NY; 89-128.
- Baxter, C.D.P., Bradshaw, A.S., Green, R.A., and Wang, J.H. Correlation between cyclic resistance and shear wave velocity for Providence silts. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE 2008, **134** (1): 37-46
- Bjerrum, L. and A. Landva. Direct simple-shear tests on a Norwegian quick clay. *Geotechnique* 1966; **16**(1): 1-20.
- Brandes, H.G. Simple shear behavior of calcareous and quartz sands. *Geotechnical and Geological Engineering* 2011; **29** (1); 113-126.
- Datta, M., Gulhati, S.K., and Rao, G.V. Engineering behavior of carbonates soils of India and some observations on classification of such soils. *Geotechnical Properties, Behavior and Performance of Calcareous Soils*, ASTM Special Technical Publication 1982; **777**; 395-404.
- De Alba, P., Baldwin, K., Janoo, V., Roe, G., and Celikkol. Elastic-wave velocities and liquefaction potential. *Geotechnical Testing Journal* 1984; **7**, (2): 77-87.
- Dobling, M. *Soil specific correlation between shear wave velocity and liquefaction resistance* 2013. Master's Thesis, University of Rhode Island.
- Dyvik, R. and Madshus, C.S. Laboratory measurements of  $G_{max}$  using bender elements. *Proceedings of the ASCE Convention in Detroit*, Michigan, 1985 (V. Kosla editor), 186-196.
- Flynn, W. *A comparative study of cyclic loading responses and effects of cementation of liquefaction potential of calcareous and silica sands*. 1997. M.S. Thesis, University of Hawaii, Manoa.
- Frydman, S., Hendron, D., Horn, H., and Steinbach, J. Liquefaction study of cemented sand. *Journal of the Geotechnical Engineering Division*, ASCE 1980; **106**, (3): 275-297.
- Lee, J.S. and Santamarina, J.C. Bender elements: performance and signal interpretation. *Journal of Geotechnical and Geoenvironmental Engineering* 2005; **131**; 27.
- Medley, E.W. *Geological engineering reconnaissance of damage resulting from the October 15, 2006, earthquakes, Island of Hawaii, Hawaii, USA*. Report available online [http://www.geerassociation.org/Post\\_EQ\\_Reports.html](http://www.geerassociation.org/Post_EQ_Reports.html) (last visited 03/13/15).
- Morales-Velez, A.C. *Evaluation of Field Based Liquefaction Approaches for Calcareous Sands Using Shear Wave Velocity*. 2014, Ph.D. Dissertation, University of Rhode Island.
- Morioka, B.T., and Nicholson, P.G. Evaluation of the liquefaction potential of calcareous sand. *Proceedings of the Tenth International Offshore and Polar Engineering Conference*, Seattle, Washington, 2000.
- Mulilis, J.P., Arulanandan, K., Mitchell, J.K., Chan, C.K. and Seed, H.B. Effects of sample preparation on sand liquefaction. *Journal of the Geotechnical Engineering Division* 1977; **103**(2): 91-108.
- Nauroy, J.F. and LeTirant, P. "Driven Piles and Drilled and Grouted Piles in Calcareous Sands", *Offshore Technology Conference*, 6-9 May 1985, Houston, Texas, Paper ID 4850-MS, 10 p
- Pando, M.A., Sandoval, E., and Cataño, J. Liquefaction susceptibility and Dynamic Properties of Calcareous Sands from Cabo Rojo, Puerto Rico. *15<sup>th</sup> World Conference on Earthquake Engineering 2012*, Lisbon, Portugal.
- Rathje, E., Bachhuber, J., Cox, B., French, J., Green, R., Olson, S., Rix, G., Wells, D., and Suncar, O. *Geotechnical engineering reconnaissance of the 2010 Haiti earthquake 2010*. Report available online

[http://www.geerassociation.org/Post\\_EQ\\_Reports.html](http://www.geerassociation.org/Post_EQ_Reports.html) (last visited 03/13/15).

Ross, M. S., and Nicholson, P. G. *Liquefaction potential and cyclic loading response of calcareous soils*. Research Report UHM/CE/95-05 1995; University of Hawaii, Manoa.

Seed, H.B., and Idriss, I.M. Simplified procedure for evaluating soil liquefaction potential. *Journal of Geotechnical Engineering*, ASCE 1971, **79**, (9): 1249-1273.

Silver, M.L., Chan, C.K., Ladd, R.S., Lee, K.L., Tiedemann, D.A., Townsend, F.C., Valera, J.E., Wilson, J.H. Cyclic Triaxial Strength of Standard Test Sand. *Journal of Geotechnical Engineering Division*, ASCE 1976; **102** (GT5); 511-523.

Tokimatsu, K., Yamazako, T., and Yoshimi, Y. Soil liquefaction evaluations by elastic shear moduli. *Soils Foundation*, 1986; **26** (1): 25-35.