Comparison of the Cyclic Resistance of a Calcareous Sand Deposit from Puerto Rico from Seismic Dilatometer (SDMT) and Seismic Cone Penetration Tests (SCPTu).

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ABSTRACT: This paper presents a comparison of the estimated cyclic resistance of a very loose, uncemented calcareous sand from Puerto Rico, USA using seismic dilatometer (sDMT) and seismic cone penetration tests (sCPTu). A soil-specific cyclic resistance-shear wave velocity relationship was developed from a series of cyclic simple shear tests with shear wave velocity measurements and was used as a baseline for comparing the results of the field-based approaches. There was better agreement between the CPT and soil-specific measures of cyclic resistance than the DMT liquefaction potential approach proposed by Monaco et al. (2005). There was also more variability in the DMT-predictions of cyclic resistance; this was attributed more to the difficulty of performing dilatometer tests in these very loose sands than limitations in the approach.

1 INTRODUCTION

The objective of this paper is to compare the cyclic resistance of a site located in the western region of the island of Puerto Rico (PR) consisting of very loose, saturated, uncemented calcareous sands estimated from dilatometer and cone penetration test results. Field testing included conventional drilling and sampling, standard penetration tests (SPT) with energy measurements, cone penetration tests with shear wave velocity measurements (sCPTu) and dilatometer tests also with shear wave velocity measurements (sDMT). A soil-specific cyclic resistance-shear wave velocity (CRR-V_{s1}) relationship was also developed from a series of K_o-consolidated, constant volume cyclic direct simple shear tests with shear wave velocity measurements on reconstituted samples collected during the site investigation. This soil-specific correlation developed in the laboratory was used as a baseline for comparison between cyclic resistance obtained in the laboratory with the cyclic resistance obtained with the CPT and DMT field-based approaches.

2 GEOTECHNICAL SITE INVESTIGATION

The site in question is located in Cabo Rojo, which is along the southwestern coast of Puerto Rico, USA (18°5'41.18"N, 67°11'41.67"W). The site consists of approximately 0.5 to 1 meters of sandy fill, 3 meters of very loose uncemented calcareous sand overlying silty clay. The water table was measured at a depth of 0.6 to 0.8 meters and was connected hydraulically to the ocean adjacent to the site.

The site was chosen both because of the presence of calcareous sands and the relatively high seismicity of the region (Bachhuber et al. 2008).

SPT, sCPTu and sDMT were performed at two locations at the site, and the profiles of tip resistance (q_t), contact and expansion pressure (p_o, p_1), shear wave velocity (V_s) and horizontal stress index (K_D) are shown in Figs. 1 and 2.

3 PROPERTIES OF CABO ROJO SAND

Calcareous sands are generally formed from the bodies of marine organism and are composed of calcium carbonate. These sands are often found in tropical and subtropical regions of the United States, including Puerto Rico, Hawaii and Florida. Typically, calcareous sands are characterized by very high void ratios, a wide variety of particle sizes and shapes, higher grain crushability, higher specific gravity, brittle stress-strain behavior, and higher compressibility compared to silica sands.

The cyclic behavior of the Cabo Rojo sand used in this study has been studied extensively by Sandoval and Pando (2012) and Morales-Velez (2014). The grain size distribution for the Cabo Rojo sand is shown in Fig. 3.

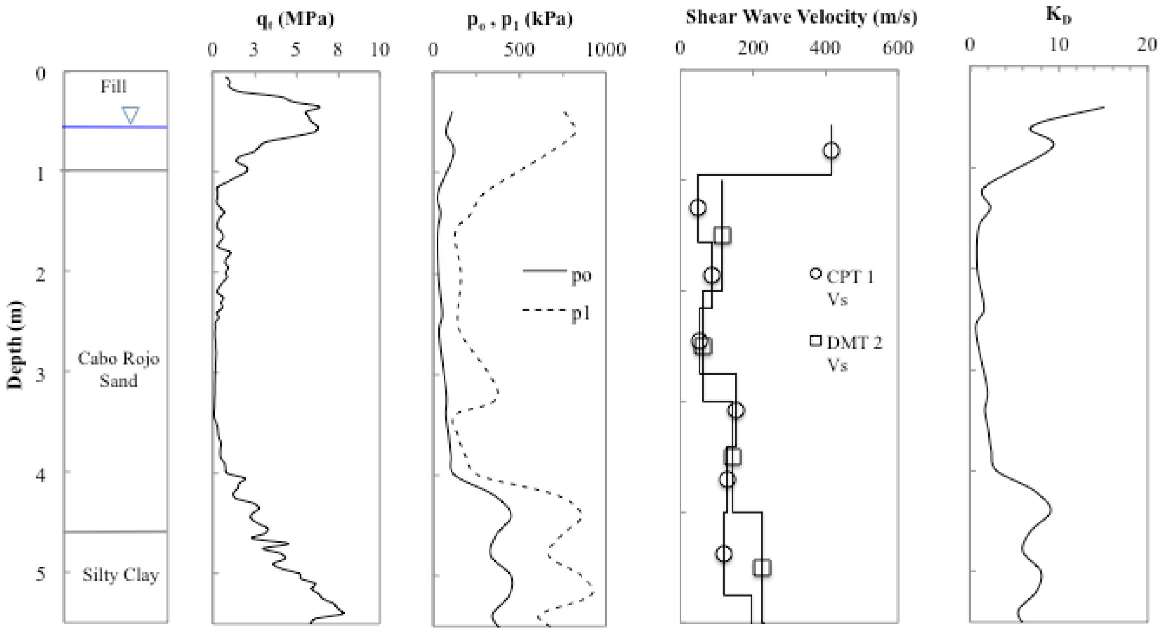

Fig. 1. Results of seismic dilatometer test and seismic cone penetration test at location 1.

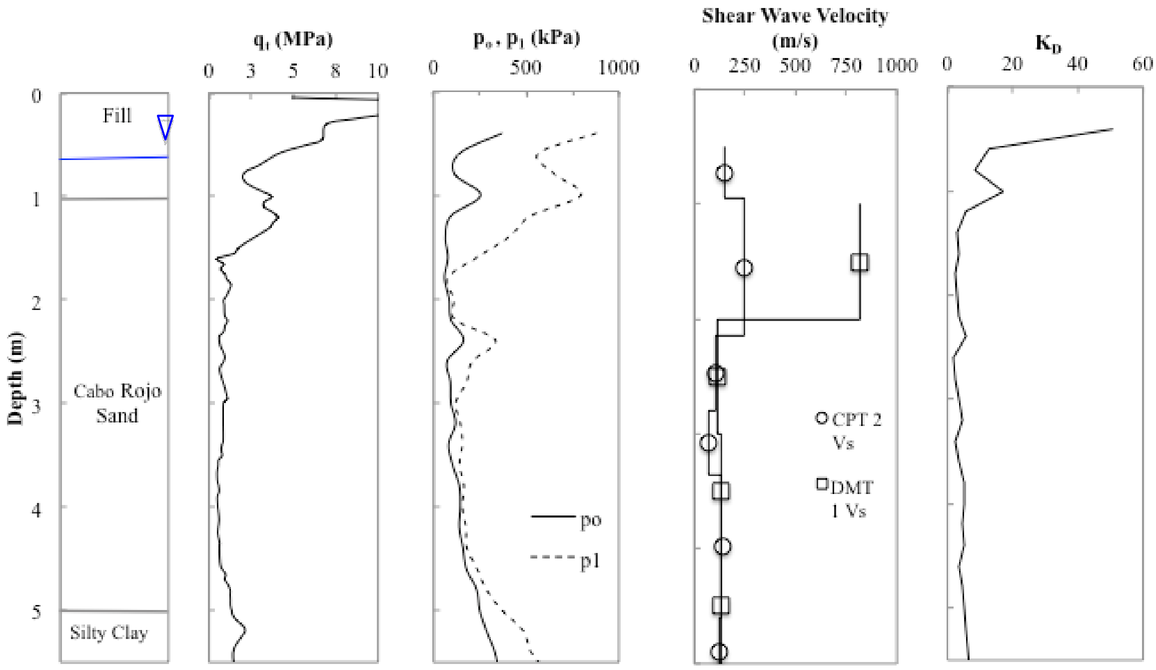

Fig. 2. Results of seismic dilatometer test and seismic cone penetration test at location 2.

The sand exhibits a fairly uniform gradation, with grain sizes ranging from 0.17 mm to 2 mm, and no fine contents. The soil is classified as a poorly graded sand (SP) according to the Unified Soil Classification System. Values of Specific Gravity (G_s), minimum and maximum density (γ_{min}, γ_{max}), and minimum and maximum void ratio (e_{min}, e_{max}) are shown in Table 1.

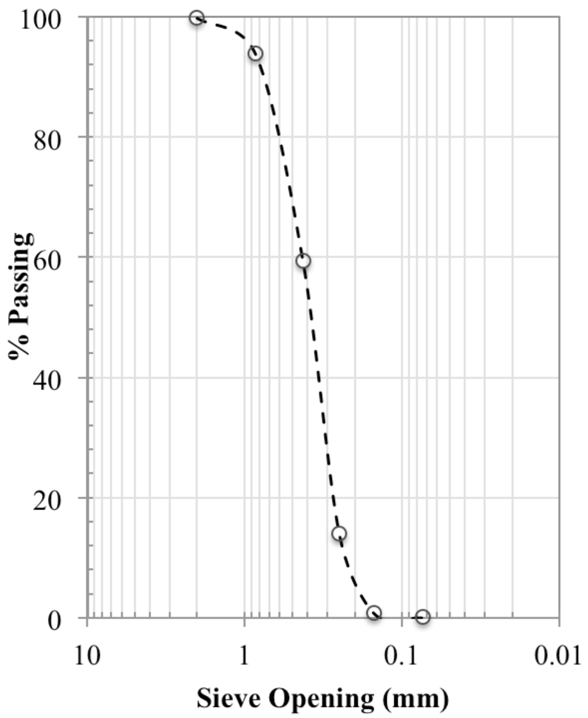

Fig. 3. Grain size distribution for the Cabo Rojo sand.

Table 1. Index properties of the Cabo Rojo sand.

Parameter		Cabo Rojo Sand	ASTM Standard
G_s		2.87	ASTM D 854-06
γ_{min}	(kN/m^3)	10.2	ASTM D 4254-00
e_{max}		1.75	
γ_{max}	(kN/m^3)	12.0	ASTM D 4253-00
e_{min}		1.34	

Fig. 4 shows scanning electron micrographs of the Cabo Rojo sand. These micrographs illustrate the very high intra particle porosity typically exhibited by calcareous sands and the wide variety of particle sizes and shapes. The Cabo Rojo sand has angular grains that are ivory to white in color and the presence of shells can be clearly observed. Mineralogical studies on the sand, such as X-Ray Diffraction and bulk carbonate content, revealed a predominance of carbonate materials such as calcite and aragonite and calcium carbonate contents greater than 95%.

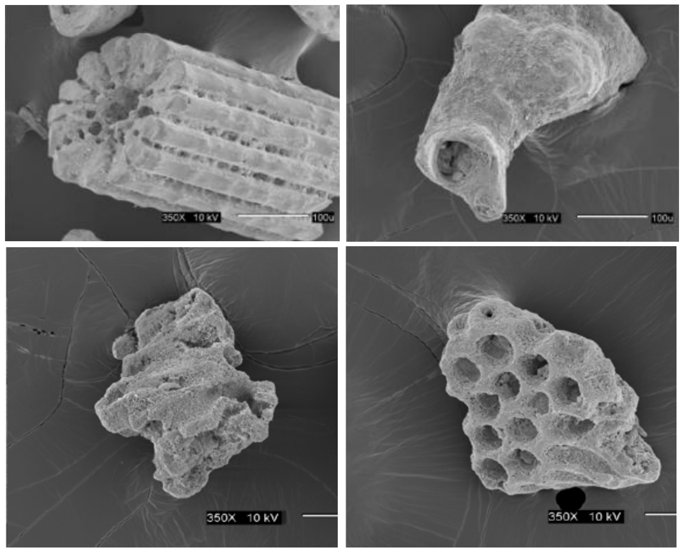

Fig. 4. Scanning electron micrographs of Cabo Rojo sand (Cataño and Pando 2010).

4 SOIL-SPECIFIC CRR-V_{S1} RELATIONSHIP

A commonly used field-based approach for assessing liquefaction potential using shear wave velocity was proposed by Andrus and Stokoe (1997). However, there is increasing evidence that the cyclic resistance-shear wave velocity (CRR-V_s) relationship is soil specific and can be used to link *in situ* test results such as CPT and SPT with laboratory determined values of CRR. This is supported by several studies in which reconstituted samples had the same cyclic behavior as frozen samples (Tokimatsu et al. 1986), high quality piston samples (Wang et al. 2006), and block samples (Baxter et al. 2008) provided the reconstituted samples were prepared to the same V_s as the undisturbed samples. For this reason, a site-specific CRR-V_{s1} correlation was developed in the laboratory for this study using the calcareous sand samples collected during the geotechnical site investigation.

Fig. 5 shows the proposed soil-specific field CRR-V_{s1} relationship for the Cabo Rojo sand compared to the Andrus and Stokoe (1997) curve. Samples were prepared at different relative densities 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.

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. The shear wave velocity was measured using end caps with bender elements specially designed and fabricated for this study. 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). The system delay was measured by putting both bender elements together (transmitter and receiver) and that time delay was subtracted from the measured signals in soils. 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.

Samples were sheared under constant volume conditions (i.e. undrained) 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%. Soil samples were prepared as either dry or moist. In a constant volume CDSS test, it is assumed that the change in vertical stress is equal to the excess pore pressure, which would have been measured in a truly undrained (Dyvik and Madshus 1985).

Laboratory values of cyclic resistance were equated to field values by taking the cyclic resistance at 15 cycles of shaking. This is considered to be equivalent to liquefaction due to a magnitude 7.5 earthquake, as suggested by Seed and Idriss (1971).

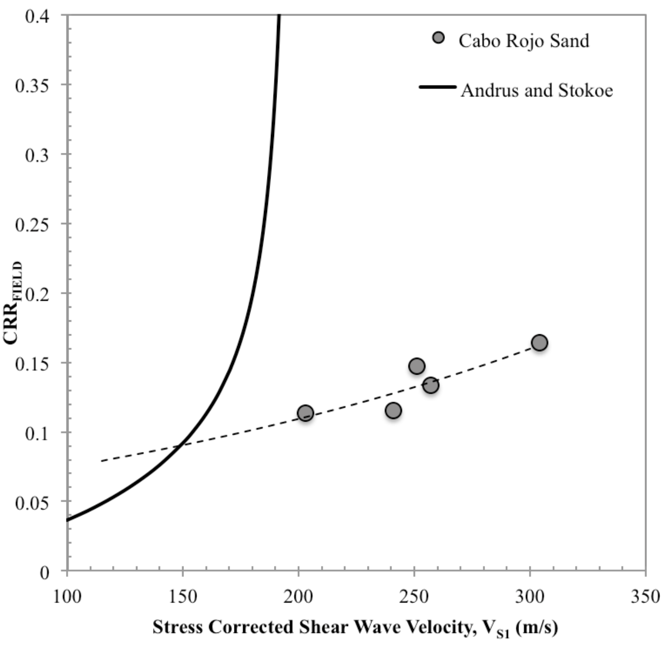

Fig. 5. Proposed in situ CRR-V_{s1} relationship for the Cabo Rojo sand compared to the field-based curve of Andrus and Stokoe (1997).

The CRR obtained by means of cyclic DSS tests was converted to field conditions by applying a multidirectionality factor of 0.9, as suggested by Seed et al. (1975). The values of V_s were corrected for overburden (normalized to σ_1' = 100 kPa).

As it can be observed from this figure, the curve obtained for the Cabo Rojo sand by cyclic DSS, is to the right of the field-based curve. This behavior suggests (1) the CRR-V_{s1} relationship appears to be soil specific, (2) the cyclic resistance appears to be independent of sample preparation methods, (3) the use of field-based curves available in the literature for all soils may not be appropriate and (4) the use of the available field-based curves for the Cabo Rojo sand may be unconservative. In other words, the results of this laboratory study suggest that the liquefaction resistance of the Cabo Rojo sand is much lower than predicted by the field-based approaches.

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). A possible explanation for the flatness of the CRR-V_s relationship for the Cabo Rojo sand is the lack of significant dilation in the denser (higher V_s) samples during shear. Some dilation was observed but it is evidently not enough to mobilize significant cyclic resistance. It is not clear why more cyclic resistance was not mobilized for the high shear wave velocity samples.

Susceptibility to crushing is a very important consideration for granular soils since it highly influences its geotechnical properties. Particle crushing is especially known to be an issue when dealing with calcareous deposits, given this material high intraparticle voids and brittle mineralogy. Particle crushing was believed to be a plausible explanation for the flatness of the CRR-V_s relationship. To evaluate the crushing potential of the Cabo Rojo sand, grain size analyses were made before and after several CDSS tests were performed. The crushing of particles was measured by comparing the grain size distribution curves obtained before and after the tests. Results indicate that there was no crushing at the stress levels used in this study. This does not mean that the calcareous sands from Cabo Rojo are not susceptible to crushing, as it will clearly depend on the stress levels and boundary conditions of each test.

Similar behavior can be observed for a variety of soils found in the literature such as the Farmer's

Markets Silts, which are non-plastic, dilatant silts found in Providence, RI (Baxter et al. 2008) and for Kawaihae sand, which is a calcareous, uncemented sand from Hawaii (Brandes 2011). In fact, the behavior observed for the Calcareous sands from Hawaii is very similar to the Cabo Rojo sand from PR, even though their grain size distributions are very different. One interesting finding is that the Calcareous sands from Hawaii also did not show significant dilation spikes during shear.

5

6 COMPARISON OF DMT AND CPT LIQUEFACTION POTENTIAL APPROACHES

This section presents a comparison of the DMT and CPT field-based liquefaction approaches for the Cabo Rojo sand using the soil-specific cyclic resistance-shear wave velocity (CRR-V_s) relationship developed in the laboratory.

Shear wave velocity was used to link the laboratory and field behavior using the following approach: (1) a V_{s1} value from the shear wave velocity profile obtained at the site investigation (either by means of sCPT or sDMT) was selected, (2) a corresponding value of CRR_{FIELD} was chosen from Fig. 5, and (3) the resulting value of CRR_{FIELD} was then compared to the CRR from the different field-based approaches. Given that the shear wave velocities obtained in the field were generally lower than those obtained in the laboratory by means of bender element testing, the CRR_{FIELD}-V_{s1} relationship was extrapolated in order to obtain values of CRR at lower shear wave velocities. This is shown in Fig. 5 for the Cabo Rojo sand by the extended black dashed line. Two CPT and two DMT soundings with shear wave velocity measurements were performed at the study site adjacent to each other, with the results shown in Figs. 1 and 2. The seismic Cone Penetration Tests (sCPTu) were performed in accordance with ASTM D5778. A Vertek® digital electronic penetrometer with a 60° apex angle, a cone area of 10 cm^2, a sleeve area of 150 cm^2 and a maximum tip force of 5 tons was used for the sCPT tests. The location of the porous element used for the pore pressure measurements was directly behind the friction sleeve (u_2 position). The seismic standard tri-axial geophone has a range of ± 2g. The sCPTu tests at the site included continuous measurements of tip resistance, sleeve resistance, pore water pressure, as well as shear wave velocity measurements at every 1-1.5 meter intervals. The cone penetrometer was pushed with a conventional drill rig at a rate of 2 cm/s. The seismic flat plate dilatometer tests (sDMT) were performed in accordance with ASTM D 6635 for this study. The dilatometer blade dimensions were 95 mm width and 15 mm thick. The cutting edge that penetrates the soil has an apex angle between 24° to 32°. The lower tapered section of the tip is 50 mm long and the blade can safely withstand up to 250 kN of pushing thrust. The circular steel membrane is 60 mm in diameter and 0.2 mm in thickness. The blade was pushed into the ground at a rate of 2 cm/s using the drill rig. Shear wave velocity measurements were taken at 1-meter intervals.

The cyclic resistance was estimated from the sCPTu data using the procedure developed by Robertson and Wride (1998) as summarized in Youd et al. (2001). This approach correlates CRR with cone tip resistance normalized (q_{c1N}) to an effective overburden stress of 1 atm (~100 kPa). Because the purpose of this study is to compare cyclic resistance only, a reference earthquake magnitude of 7.5 was used. The cyclic resistance was estimated from the sDMT data using the relationship proposed by Monaco et al. (2005). Cyclic resistance was related to the horizontal stress index by combining existing CRR-K_D curves along with experience incorporated in current available methods based on SPT and CPT data, and this relationship is shown in Fig. 6 and Eq. 1. Monaco et al. (2005) compared their approach to field performance from different sites that experienced liquefaction and had been characterized using the DMT. The CRR-K_D relationship in Fig. 4 is applicable for a M_w = 7.5 earthquake and clean sand sites.

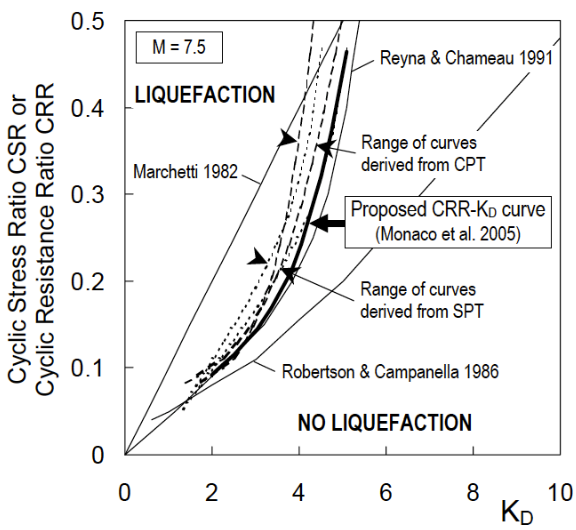

Fig. 6. CRR-KD curves for evaluating liquefaction resistance from DMT (Monaco et al. 2005).

$CRR_{DMT}=0.0197K_D^3-0.0741K_D^2+0.2169K_D-0.1306$ (1)

Fig. 7 shows the estimated CRR profiles from both sCPTu-1 and sCPTu-2 profiles and the soil-specific CRR_{FIELD}-V_{s1} relationship. Based on the low values of skin friction in sCPTu-1 and sCPTu-2 and soil samples, the calcareous sand layer is up to 4 meters in depth. As shown in this figure, the soil-specific CRR-V_s relationship developed by means of CDSS is in reasonable agreement with the cyclic resistance obtained with the field-based approaches developed Robertson and Wride (1998). Based on the data from sCPTu-1 up to 2.5 m in depth, the field-based approach over-predicted the cyclic resistance slightly over the soil-specific cyclic resistances. At greater depths, the soil-specific correlation slightly over-predicts the cyclic resistance obtained by the field-based approach. Based on the data from sCPT-2, the agreement between the field-based approaches and the soil specific was good. Fig. 8 shows the estimated CRR profiles from both sDMT-1 and sDMT-2 profiles and the soil-specific CRR_{FIELD}-V_{s1} relationship. For sDMT-1, it can be observed that the field-based procedures overestimated the cyclic resistance of the soils found at the site, at all depths. For sDMT-2, at very shallow depths, from the surface down up to 0.5 meters, the cyclic resistance obtained with the field-based approach is very high (not shown). This DMT sounding was made near the parking lot area of the beach area. An explanation to this high CRR value (>5.0) could be that soils were compacted by the traffic loading or that the surficial calcareous sands in this area were cemented. Also, the shear wave velocity measurement at this depth is abnormally high (>1,000 m/s). Even though this value is definitely not expected in soils, and could be potentially attributed to a faulty reading, it is consistent with the high values of horizontal stress index. From a depth of 1 to 4 meters where the calcareous layer is found there is good agreement with the field-based approach and the correlation developed in the laboratory by means of CDSS. The variability between sDMT-1 and sDMT-2 might have been due to issues in operating the dilatometer at that location. The horizontal stress index obtained for sDMT-1 is higher than the one obtained for sDMT-2. The overestimation of the cyclic resistance of sDMT-1 in comparison with sDMT-2 is consistent with the higher values of the horizontal stress index (K_D) shown in Fig. 2.

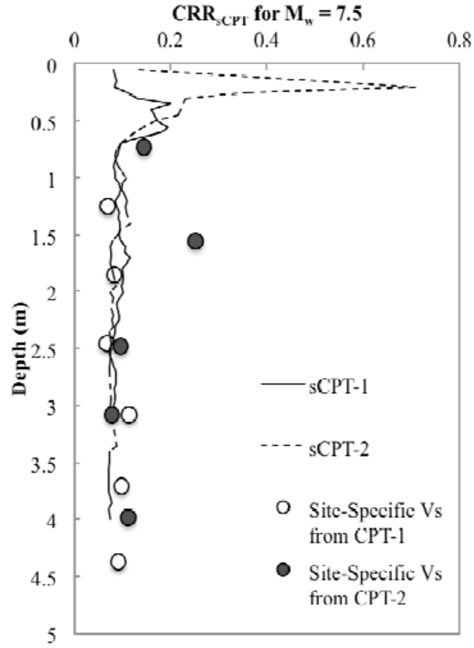

Fig. 7. Cyclic resistance of the Cabo Rojo sand using the CPT-field based approach and the site-specific analysis.

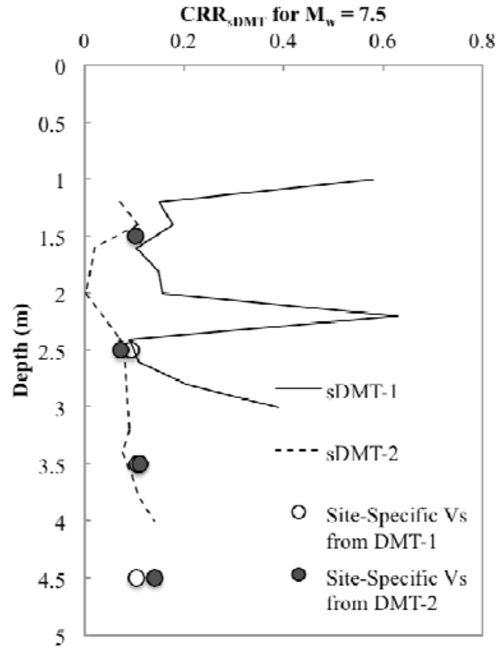

Fig. 8. Cyclic resistance of the Cabo Rojo sand using the DMT-field based approach and the site-specific analysis.

Overall, the cyclic resistance to liquefaction obtained by both methodologies is very low in the calcareous layer. This is expected given the low tip resistances and low horizontal stress indices found in these sands. Values of low horizontal stress index can potentially indicate: (1) loose sands, (2) uncemented sands, (3) low K_o environment and (4) little to no stress history in the deposit. A sand deposit with all of these conditions is expected to liquefy under cyclic loading. All of these factors were consistent with data collected from SPT, sampling and CPT tests.

7 SUMMARY AND CONCLUSIONS

Liquefaction potential is most often estimated in practice using field-based correlations involving standard penetration tests, cone penetration tests, or *in situ* measurements of shear wave velocity. More recently, however, field-based approaches for assessing cyclic resistance have been proposed using the dilatometer test.

The objective of this study was to compare the estimated cyclic resistance of a very loose, uncemented calcareous sand deposit from the island of Puerto Rico, USA using the seismic cone penetration test (sCPTu) and the seismic dilatometer test (sDMT). A soil-specific cyclic resistance-shear wave velocity relationship was also developed from a series of cyclic simple shear tests with shear wave velocity measurements and was used as a baseline for comparing the results of the field-based approaches. Shear wave velocity was used to link the laboratory and field data. Overall, the soil-specific CRR-V_s relationship developed by means of CDSS is in reasonable agreement with the cyclic resistance obtained with the sCPTu field-based approach. The DMT field-based approach slightly overestimated the CRR of the soils found at the site, although this may be due to the difficulty of performing dilatometer tests in these very loose sands rather than limitations in the approach.

8 ACKNOWLEDGMENTS

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