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ABSTRACT

An experimental study based on Static Cone Penetration Tests (CPT) performed in Calibration Chamber (CC) and cyclic Simple Shear (SS) tests was undertaken in order to establish a correlation for estimating cyclic resistance ratio (CRR) of calcareous sands. CPT's in CC were carried out on an uncemented calcareous sand, dug out from Brittany in France (Quiou sand) in the context of a previous research. Test results were thus re-analysed by the authors, considering the specific purposes of the paper.
SS tests were conducted on specimens reconstituted by water sedimentation method that, according to the authors' previous studies is capable of reproducing more realistically than other methods, the in-situ response of natural deposits of marine or fluvial origin.
Test results showed that CRR vs. normalized cone penetration resistance ($q_{c1,N}$) data points fall just above correlation curves, recommended in the literature for the assessment of liquefaction potential of clean silica sands. The approach based on relative state parameter concept embodied in current semi-empirical liquefaction correlations was also verified for the tested sand.

INTRODUCTION

Assessment of seismically induced soil liquefaction is an important task for geotechnical design practice. Because of the difficulties and limitations associated with retrieving high quality undisturbed sand samples, the use of in-situ testing is widely adopted in geotechnical practice. The CPT is an ideal in situ test to evaluate the potential for soil liquefaction because of its repeatability, reliability, continuous data and cost-effectiveness [Robertson, 2004].

It is worth mentioning that most of the existing CPT-based correlations for liquefaction resistance assessment are valid for silica sands from low to medium compressibility. However, mineralogical features of sands can have significant effects on both cone penetration resistance (q_c) and cyclic resistance ratio (CRR), and may affect the resulting CRR- q_c relationship.

In particular, this issue concerns calcareous sands in virtue of their crushable nature; however a rather small body of CPT liquefaction data based on field performance are available for them.

Based on the above considerations, it has been deemed useful to use static Cone Penetration Tests (CPT) performed in Calibration Chamber (CC) and cyclic Simple Shear (SS) or triaxial (TX) tests to search for appropriate correlations for calcareous soils. This approach was previously applied by several researchers for developing direct relationships between q_c and liquefaction strength of silica sands [Baldi *et al.*, 1985; Iwasaki *et al.*, 1988; Porcino & Marcianò, 2009b) or silty sands [Huang & Huang, 2006). In particular, the results gathered by Porcino & Marcianò [2009b] on a clean medium silica sand (Ticino sand) appear satisfactory. They evidenced that the correlation between the cyclic resistance ratio evaluated in SS tests and the normalized CPT tip resistance ($q_{c1,N}$) measured in the CC tests, corresponds well to the recommended field-performance-based correlation for clean silica sands [Idriss & Boulanger, 2004).

The advantage of calibration chamber testing is to study the response of CPT in well defined and well controlled conditions of relative density, initial stress state, OCR and sample boundary conditions. On the other hand, it is well known that simple shear tests closely replicate the loading conditions induced by an earthquake in a natural soil deposit.

In the light of the above, the authors performed in the current paper an experimental study on a calcareous sand from a marine French deposit (Quiou sand).

Undrained cyclic strength characteristics were assessed from cyclic SS tests carried out in a modified NGI type apparatus on specimens prepared by water sedimentation (WS) method, taking into account various density states. Such a reconstitution method is deemed to replicate well the behaviour of undisturbed samples recovered from natural deposits of marine or fluvial origin [Ghionna & Porcino, 2006; Porcino & Marcianò, 2008a].

The results of CPT's performed in the CC samples of the same sand, carried out at ENEL CRIS of Milan and ISMES of Bergamo in the context of a previous research, were considered to seek a relationship between liquefaction strength and penetration resistance.

Finally, a comparison between the resulting correlation applicable to uncemented carbonate sands and the recommended CPT- based correlations for silica sands, is provided.

TESTING MATERIAL

Experimental investigation was performed on Quiou sand (QS) [Bellotti *et al.*, 1991; Golightly, 1989; Porcino *et al.*, 2008b, 2009a), a skeletal uncemented carbonatic sand of biogenic origin dug-out from Brittany (France). The mineralogical and physical features of this sand are presented in table 1 while the gradation curve is shown in Fig. 1.

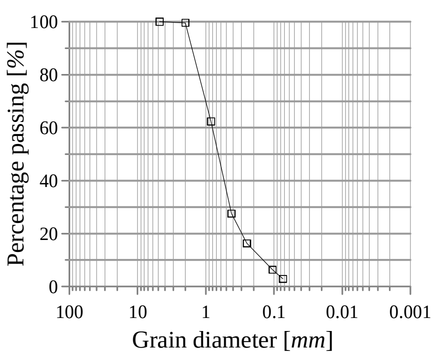

Fig. 1. Grain size distribution curve of Quiou sand.

Table 1. Mineralogical and physical features of tested sand.

Parameter		*Mineralogical composition*	
D_{50} [mm]	0.75	Shell fragments [%]	73.5
U_c	4.4	Calcium carbonate aggregates]%]	14.5
e_{max}	1.282	Quartz [%]	11.8
e_{min}	0.833	Rock fragments]%]	0.2
G_s	2.71		

Compressibility and crushability characteristics of tested material were assessed through one-dimensional compression tests [Bellotti *et al.*, 1991]. Some results are presented in Fig. 2. The normal compression line (NCL) determined from these results is also evidenced.

Drained triaxial compression shear tests were also performed, allowing the critical state line (CSL) to be defined in void ratio/ stress space, as shown in Fig. 2. Data points in Fig. 2 refer to the ultimate state of the tests, corresponding to the attainment of axial strains equal to or higher than 25%. It is interesting to observe that, in the investigated range of stresses, the two lines (NCL and CSL) appear quite parallel.

With the aim of evidencing the influence of mineralogy on the derived CPT- based correlation for liquefaction resistance assessment, a reference well known silica sand, namely Ticino sand (TS), was considered. Grain size features of TS and QS correspond well with each other. Further details on TS characteristics can be found in Jamiolkowski *et al.* [2001] and have also been reported by the authors in a companion paper presented to another Conference [Porcino & Marcianò, 2009b].

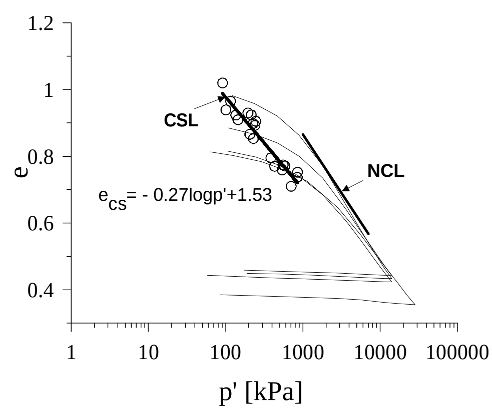

Fig. 2. Normal compression line (from one-dimensionally compressed samples) and critical state line in e:logp'space for Quiou sand.

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CPT'S IN CALIBRATION CHAMBER

Equipment and Testing Procedure

The results of Calibration Chamber tests presented herein were gathered in the context of a previous cooperative experimental research carried out at ENEL CRIS of Milan and ISMES of Bergamo, involving two CC's ("small": diameter (D_c)=0.60 m and height (H_c) = 1.0 m; "large": D_c =1.20 m and H_c = 1.50 m).

Test results were re-analysed by the authors taking into account the specific objectives of the paper.
Chamber specimens were prepared by means of pluvial deposition in air [Bellotti *et al.*, 1982, 1988; Almeida *et al.*, 1991] in the range of D_r=40-100%,

After formation, the sand specimen was subjected to one-dimensional consolidation under k_0 condition. All penetration tests considered in this study were carried out on normally consolidated (NC) specimens. CPT's were performed in both dry and saturated conditions.

Furthermore, two electrical cone penetrometers of different size cone diameters (d_c) were adopted for the tests in the two CC, namely a standard cone (d_c =35.7 mm) for tests in the large CC and a smaller cone (d_c =20 mm) for tests in the small CC. For the CPT's carried out in the two CC this corresponds to an R_d ratio, between CC sample diameter (D_c) and cone diameter (d_c), approximately equal to 33.6 and R_d=30 in the large and small CC, respectively.

Additionally, the penetrometer tips were equipped with a special hardened steel porous stone for pore pressure measurement during penetration.

More details concerning CC features and test procedures can be found in previous works by Bellotti *et al.* [1982, 1988], Bellotti & Pedroni [1991], Ghionna & Jamiolkowski [1991], and Ghionna *et al.* [1994].

Both CC's were specially designed to perform tests under strictly controlled boundary conditions (BC) both in terms of stresses and strains. Depending on whether stresses are kept constant or displacements are zero at the lateral and bottom sample boundaries, four different types of boundary conditions can be applied during the penetration stage, namely B_1(σ_v=const, σ_h=const), B_2 ($\Delta\varepsilon_v$=$\Delta\varepsilon_h$=0), B_3 ((σ_v=const, $\Delta\varepsilon_h$=0) and B_4 ($\Delta\varepsilon_v$=0, σ_h=const).

However, none of these four boundary conditions simulate the field conditions perfectly but they can define an interval in which the real in situ values can be searched. The effect of chamber size and boundary condition on the tip resistance has been widely investigated by several researchers based on both experimental and numerical analyses [Almadi & Robertson, 2004; Ghionna & Jamiolkowski, 1991; Jamiolkowski *et al.*, 1985; Lunne & Christophersen, 1983; Mayne & Kulhawy, 1991; Parkin & Lunne, 1982; Salgado *et al.*, 1998].

In particular, these studies confirmed that such effects are inversely proportional to R_d ratio and reduce for loose sands or sands which are more compressible in nature (i.e. calcareous sands vs. silica sands). As outlined by Jamiolkowski *et al.* [2001], for the tested calcareous sand the effect of the chamber size and boundary conditions can be considered negligible [Fig. 3]. for both small and large CC's.

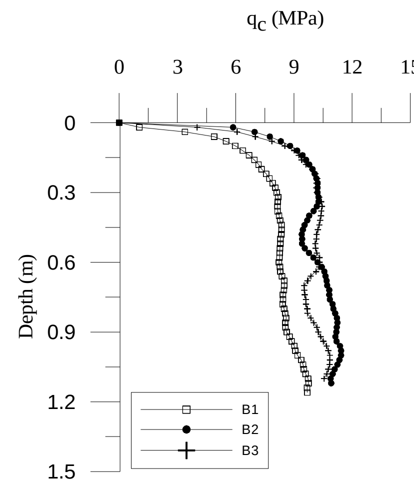

Fig. 3. Influence of boundary conditions on penetration resistance of dry carbonatic Quiou sand (tests performed in large CC on very dense specimens)

Furthemore, pore pressure measurements (Δu) in saturated specimens [Almeida *et al.*, 1991] suggested that the cone penetration in the tested sand may be considered virtually a drained test since the associated pore pressures are far lower than the corresponding tip resistances. Figure 4 shows the comparative response of dry vs. saturated specimens on the measured values of tip resistance in Quiou sand. It is apparent that the effect of saturation condition can be neglected for both loose and dense CC specimens.

Representative values of q_c monitored at a depth equal to 0.75 m from the top surface of the sample were used in the analysis.

It is noteworthy to mention that particle breakage caused by cone penetration was generally observed by determining changes in the grading curve prior to and after testing around the cone path [Almeida *et al.*, 1991; Bellotti *et al.*, 1991].

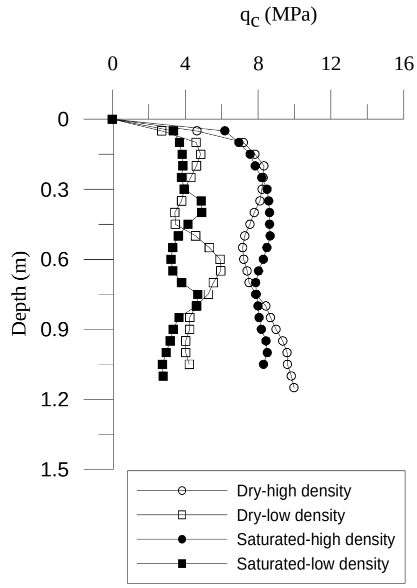

Fig. 4. Influence of saturation conditions on penetration resistance of carbonatic Quiou sand (tests performed in large CC)

Correlation between q_c and relative density for calcareous sand

Based on previous studies on silica sands [Jamiolkowski *et al.*, 2000, 2001], the following equation was used as a framework to establish an empirical correlation between cone resistance, relative density and effective vertical stress (σ'_{v0}) for the calcareous sand (NC specimens):

$$q_c = C_0 \cdot p_a \cdot \left(\frac{\sigma'_{v0}}{p_a}\right)^{C_1} \cdot \exp^{C_2 D_r} \quad (1)$$

where:

P_a is a reference pressure in the same units used for σ'_{v0} (i.e. 98,1 kPa).

C_0, C_1, C_2 are empirical correlation factors, determined by matching equation (1) to the CPT data. through a regression analysis.

D_r= relative density (as decimal).

Truly normalized (i.e. dimensionless) cone penetration resistance can be derived through the expression:

$$q_{c1,N} = C_0 \cdot \exp^{C_2 D_r} \quad (2)$$

The computed values of the coefficients in eq. (1) and (2) were listed in table 2 together with those previously determined for Ticino sand [Fig. 4].

Table 2. Coefficients of eq. (1)

Sand	*Coefficients*		
	C_0	C_1	C_2
Quiou	27.49	0.65	1.50
Ticino (*)	17.74	0.55	2.90
(*) Jamiolkowski *et al.* [2001]			

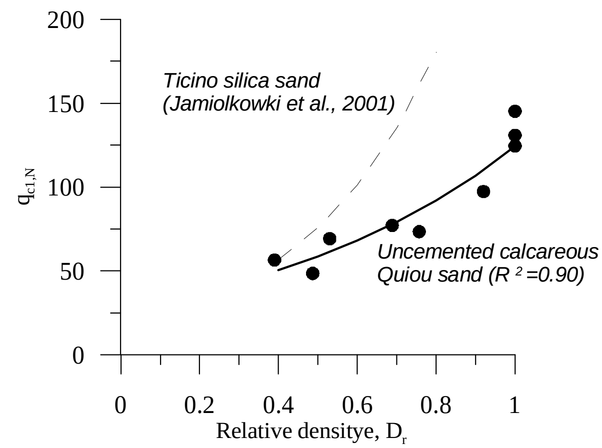

Fig. 4. Experimental correlation Dr-$q_{c1,N}$ for Quiou sand .

It is worth mentioning that the value of the constant stress exponent (C_1) of the relationship (1) is in the range of values indicated for the same sand at different relative densities by other authors (C_1=0.65 to 0.77) [Nauroy & Golightly [1990] (end bearing of driven piles), Salgado [unpublished data] (numerical analyses of cone penetration resistance)].

In Fig. 4 , the normalized tip resistances of Quiou and Ticino sands were compared at equal values of relative density. As expected, it appears that at an equal value of D_r, the cone resistance of (TS) is appreciably higher than that of (QS), this difference increases with increasing relative density. This can be attributed to the structural weakness of carbonate sand particles which makes the sand highly crushable reducing the contribution of dilatancy to strength.

In particular, at an effective vertical stress of 100 kPa, q_c(TS)/q_c(QS) ratio was found to be equal to 1.29 for D_r=50%; this ratio becomes equal to 1.95 for higher densities (D_r=80%), supporting the general findings previously reported by other authors [Almeida *et al.* [1991] and Van Impe & Verasteguif [2001]].

Lastly, it is worth mentioning that concepts such as relative density should be employed with some caution in the analysis of tests on carbonate sands, due to the uncertainties associated with the test procedure applied for the determination of maximum and minimum void ratios and the sensitivity of such parameters even to small changes in grading characteristics.

LABORATORY EVALUATION OF CYCLIC LIQUEFACTION RESISTANCE

Equipment and Testing Procedure

Undrained cyclic stress-strain and strength characteristics of QS sand were evaluated through cyclic stress-controlled simple shear (SS) tests. A modified NGI type apparatus operated by an automated control system was used in the present research [Porcino *et al*. 2006]. The apparatus houses cylindrical samples, 80 mm in diameter and 20 mm in height, laterally confined by a reinforced rubber membrane (k_0 condition). Undrained tests were performed under "constant volume" conditions [Finn, 1985; Dyvik *et al.*, 1987], adjusting the vertical stress in order to maintain the height of the sample unchanged during the shearing phase.

Specimens were reconstituted at different relative densities in a selected range from D_r=30% to 85%. Taking into account the marine origin of the calcareous deposit, water-sedimentation method was properly adopted for specimen preparation.

After one-dimensional consolidation at an effective vertical $\sigma'_{v0} = 100\, kPa$, where there is the most interest in soil liquefaction potential assessment, undrained cyclic tests were performed at a frequency of 0.02 Hz.

Data Interpretation

Figure 5 sketches typical results of cyclic SS undrained tests carried out on loose QS sample, in terms of:
- shear strain against number of cycles [Fig. 5b] and development of excess pore water pressure, normalized to σ'_{v0} $(R_u = \Delta u / \sigma'_{v0})$ [Fig. 5a],
-stress-strain hysteresis loops [Fig. 5c];
-effective stress-path [Fig. 5d].

As can be noted in Fig. 5a, in the early stages of cyclic stress application, a significant build-up of pore water pressure is observed with a negligible development of shear strains. It is only after 10 cycles that the sample begins to undergo large cyclic shear strains [Fig. 5b]. It is a common practice to define the "point of liquefaction" in cyclic SS tests as the time at which the sample reaches a 3 to 4% single amplitude shear strain (γ_{SA}) [Seed *et al.*, 2003] .

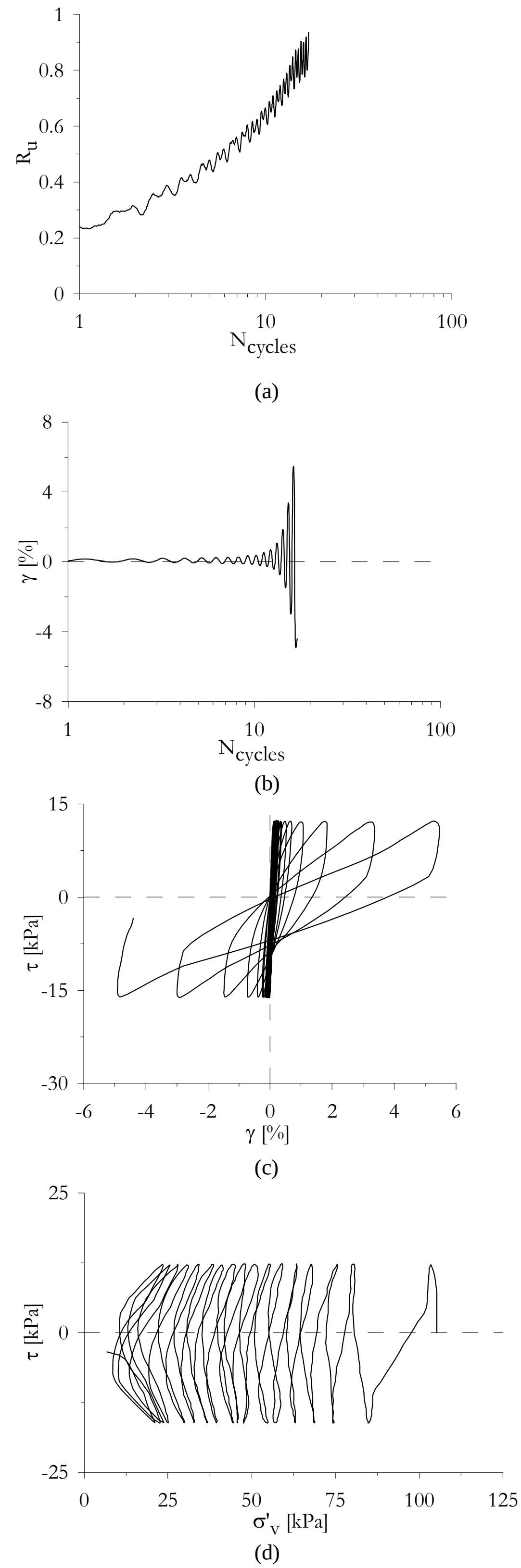

Fig. 5. Typical undrained cyclic simple shear test results on Quiou sand [D_r=43 %, σ'_{v0}=100 kPa).

At this level of shear strain, a value of R_u equal to 0.95 was attained in the performed tests.

As the test proceeds and σ'_v reduces, the shear stiffness clearly reduces [Fig. 5c].

Figure 6 depicts the relationship between cyclic resistance ratio (CRR) against relative density gathered from SS tests on QS where $CRR = \tau_{cyc} / \sigma'_{v0}$ corresponds to 15 uniform cycles of loading to cause a single amplitude shear strain of 3.75%. For comparison purposes the same figure also includes the data of Ticino sand.

It is apparent that Quiou sand has a marginally higher undrained cyclic strength than Ticino sand up to a relative density approximately equal to 70% and comparable (or even slightly less) at higher densities.

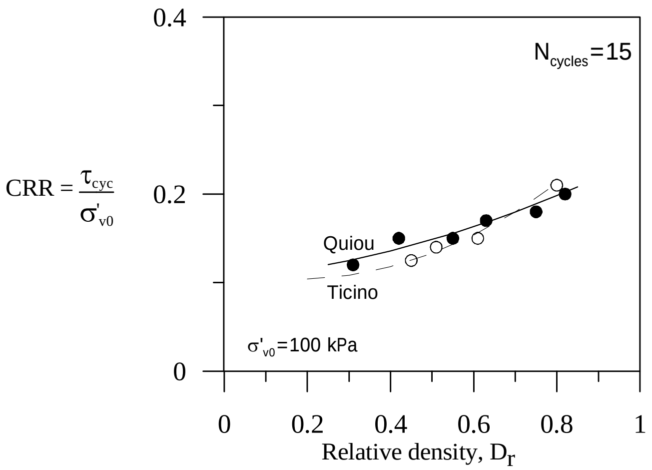

Fig. 6. Relationship between cyclic resistance ratio and relative density from SS tests on Quiou sand.

CRR-q_C RELATIONSHIP

The values of cyclic resistance ratio CRR from undrained cyclic SS tests needed to reach a selected failure criterion (γ_{SA}=3.75%) in 15 loading cycles [Fig. 6] were used to establish the CRR-$q_{c1,N}$ correlation, as shown in Fig. 7.

To take into account the effect of multi-directionality of cyclic loading in seismic events, the CRR_{field} were estimated from cyclic SS test results applying a correction factor equal to 0.9, originally proposed by Seed *et al.* [1975] for fine to medium silica sands but commonly adopted by other authors for soil with different grain characteristics.

The corresponding $q_{c1,N}$ values were then computed according to equation [2].

For comparison, additional data of cyclic SS tests on silica Ticino sand reported in Porcino & Marcianò [2009b] are also included in the same figure. It is worth mentioning that for TS the exponent (C_1) of the normalization factor was assumed to vary linearly with D_r, according to Idriss & Boulanger [2004] :

$$m = 0.784 - 0.521 \cdot D_r \quad (3)$$

Eq. (3) was derived by the above authors from CPT penetration theory and calibration chamber test data.

The results shown in Fig. 7 indicate that data points relative to calcareous sand fall to the left of the CPT-field based curves for clean silica sands proposed by NCEER [1997] and recently re-vised by Idriss & Boulanger [2004].

Taking into account the marginal differences in CRR exhibited by the two sands at equal values of relative density, as shown in Fig. 6, the results reported in Fig. 7 can be mainly attributed to the lower q_c values exhibited by calcareous sand in comparison to silica sand at the same relative density. Accordingly, the use of CPT- based correlations recommended for silica sands appears to provide a slightly conservative estimation of the liquefaction resistance of calcareous sands.

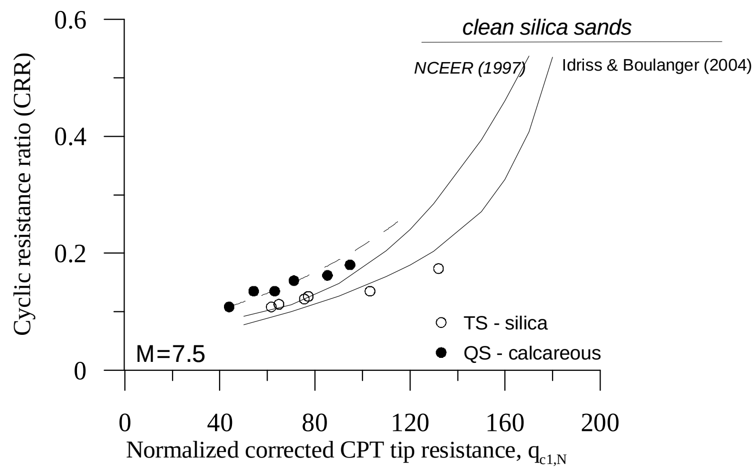

Fig. 7. Laboratory/field CPT correlations for estimating cyclic liquefaction resistance.

CRR-RELATIVE STATE PARAMETER INDEX (ξ_R) RELATIONSHIP

Despite the “unusual” geotechnical features of calcareous sediments (random and generally weak to moderate cementation, angularity of grains, high void ratios and grain crushing) the behaviour of calcareous sands is consistent with the mean features of critical state soil mechanics [Coop & Airey, 2003; Coop, 2005].

For this reason, following a critical state framework, the results of the cyclic SS tests performed on QS, were examined in terms of the relative state parameter index (ξ_R) proposed by Boulanger [2002, 2003]. They were also examined in terms of the normalized state parameters (Ψ_N) used by many authors [Been & Jefferies, 1986; Hird & Hassana, 1986; Jamiolkowski, 1990; Konrad, 1997] for which an accurate estimation of the reference line of sand [steady state (SS) /critical state (CS) line] from laboratory tests is required.

The state parameter is a useful concept since it enables us to combine the influence of both void ratio and mean effective stress on penetration resistance and liquefaction behaviour of sands.

The relative state parameter index (ξ_R) is defined as the difference between the current D_r and the critical state D_r, denoted $D_{r,cs}$, by an expression based on Bolton's [1986] relationship:

$$\xi_R = D_{r,cs} - D_r = \frac{1}{Q - \ln\left[\frac{100 \cdot p'}{p_a}\right]} - D_r \quad (4)$$

in which:

- p' is mean effective normal stress , $= \sigma'_{v0} \cdot (1 + 2 \cdot k_0)/3$, k_0 = earth pressure coefficient " at rest". For evaluating p', an average value of $k_{0=}$= 0.40 was assumed for all tested relative densities based on the results of the one-dimensional consolidation stage carried out in CC.

- p_a is atmospheric pressure (i.e. 98.1 kPa).

Q is an empirical constant, depending on the crushability features. It grows with increasing resistance to crushing and is equal to 10 or more for silica sands. As carbonate sands are crushable, we can expect Q to be smaller for them. A value equal to 7.5 was assumed for QS in equ. (4), as suggested by Randolph *et al.* [2004] for this sand.

Using such a value of Q, a good correspondence was obtained between ξ_R evaluated by eq. (4) and Ψ_N evaluated through data in Fig. 2 with the further assumption that SSL does coincide with CSL. This good correspondence can be considered an indirect validation of the value of Q assumed in the analysis for QS.

In Fig. 8. the relationship between CRR and ξ_R, derived from SS tests on Quiou sand is reported, together with the same relationship derived from previous SS tests on Ticino sand [Porcino & Marcianò, 2009b]. As can be noted, CRR-ξ_R curve for Quiou sand lies slightly above that suggested in the literature for clean silica sands confirming the general trend observed in Fig. 7.

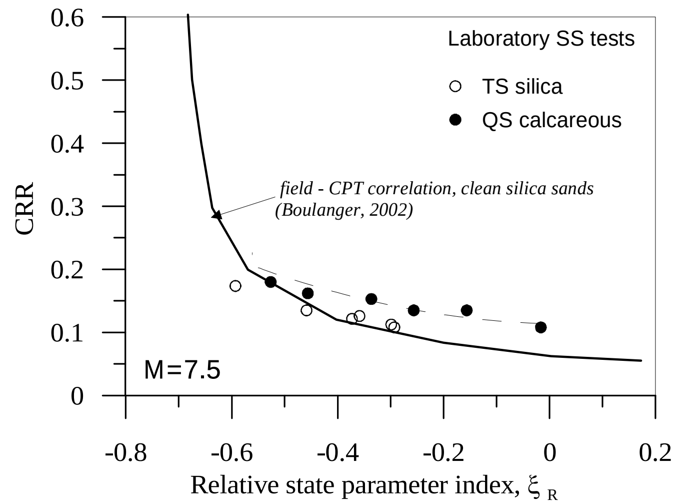

Fig. 8. CRR vs. ξ_R relationship from laboratory and field.

CONCLUSIVE REMARKS

In an effort to develop appropriate CPT-based correlations for the assessment of cyclic resistance ratio (CRR) of calcareous sands, the results of CPT's performed in calibration chamber (CC) and cyclic simple shear (SS) tests carried out on Quiou sand, an uncemented carbonate sand of biogenic origin from Britanny in France, were presented in the present paper.

Key aspects of this study are: (1) choice of the water-sedimentation method for the reconstitution of SS specimens (D_r from 30 to 85%), in order to better simulate the fabric of some natural deposits (fluvial or marine origin); (2) use of an approach, based on a constant stress exponent for the normalization of cone resistance to effective overburden stress, obtained from regression analyses of CPT's in calibration chamber; (3) use of two different approaches for correlating CRR against state parameter: It is worth mentioning that the essential feature of this parameter is that it considers the combined effect of the relative density and the initial overburden effective stress on CRR.

The following main points have emerged from the analysis of the results:

- CRR vs. normalized cone penetration resistance ($q_{c1,N}$) data points derived from laboratory tests on Quiou sand fall in the upper region of the proposed liquefaction resistance curves for clean silica sands, the latter consequently providing a conservative estimation of the cyclic liquefaction resistance of uncemented calcareous sands (i.e. differences are from 25% to 40%). The observed response is mainly associated with the fact that, at an equal D_r value, cone resistances of calcareous sands are significantly lower than those of silica sands.

- Cyclic SS test results were presented in terms of CRR vs. relative state parameter index (ξ_R) relationship. This parameter, which is based on Bolton's [1986] relative dilatancy index, was initially introduced by Boulanger [2002, 2003] and applied to silica sands for liquefaction resistance assessment.

It was found that the highly compressible nature of tested calcareous sand affects the resulting CRR- ξ_R relationship which lies slightly above that proposed in literature and applicable to clean silica sands.

- Lastly, the authors hope that more CPT tests will be carried out in other carbonate sands to constitute a solid database on which to base future analysis and correlation.

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