Shear Wave Velocity-Based Assessment of Liquefaction Resistance of Carbonate Sands

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Abstract − **Owing to some peculiar properties of "unusual" calcareous sands, most of which is linked to grain crushability, an accurate evaluation of liquefaction resistance (CRR) of such sediments requires the development of new soil-type specific relationships.**
An experimental laboratory study based on undrained cyclic simple shear (SS) tests and bender element (BE) tests in triaxial apparatus was performed on a biogenic uncemented carbonate sand, Quiou sand, dug out from a site close to Plouasne (Brittany region, France), in order to seek a relationship between CRR and normalized shear wave velocity (V_{s1}). Sand specimens were reconstituted for a range of relative densities varying between 30% and 85% by water sedimentation method. The influence of factors affecting V_s and CRR measurements, such as initial void ratio, effective confining stress and reconstitution method were investigated and discussed. The results obtained in the present research together with those of previous studies evidence that the liquefaction resistance of carbonate sands is lower than that predicted by the field-based curves drawn for corresponding silica sands.

I. INTRODUCTION

Shear wave velocity measurements provide valuable soil information, which is relevant to a wide range of engineering tasks including the design of foundations subjected to dynamic loading, process monitoring, liquefaction assessment, and soil improvement control. As far as liquefaction resistance is concerned, it is well recognized that the currently used shear wave velocity-based liquefaction potential curves were developed from field-performance studies of silica sandy soils [1] and that among the in-situ "index" tests (SPT, CPT, V_s), shear wave velocity seem to produce good and reliable correlations with liquefaction resistance even for crushable soils [2]. As pointed out by Seed and Idriss [3],

with field seismic conditions being properly simulated, the controlled laboratory studies can be used to broaden the applicability of liquefaction criteria, especially for the conditions where little to no field performance data is available. Thereafter, many studies have been focusing on this subject with reference to clean sands [4,5,6] and sand-silt mixtures with non-plastic fine [7,8], demonstrating the validity of laboratory V_s-based methods for liquefaction resistance assessment.

The main purpose of the present study is to establish a reliable relationship between normalized shear wave velocity and liquefaction resistance for a biogenic calcareous sand of marine origin based on a laboratory investigation. To meet this objective, a cyclic modified NGI simple shear apparatus and bender element tests were accurately performed on sand specimens reconstituted by water sedimentation method for a range of initial void ratios. Based on this approach, a well-defined CRR–V_{s1} correlation is established for the tested carbonate sand and a comparison with the existing V_s-based correlations for clean silica sands is also presented.

II. LABORATORY TESTING

A. Test material and procedures

Bender element (BE) tests and cyclic undrained simple shear (CSS) tests were carried out on reconstituted specimens of Quiou sand (QS) [9,10]. It is classified as being medium to coarse, poorly graded sand (SP), with subangular to subrounded grains. It is a biogenic (skeletal) uncemented carbonate sand, dug out from a borrow pit close to the village of Plouasne in Brittany (France). Physical and mineralogical properties of tested sand are listed in Table 1.
Triaxial and SS specimens were prepared by using water sedimentation (WS) technique which resulted in a similar response to undisturbed sandy-gravelly soils of marine or fluvial origin recovered by in-situ freezing [11,12].

Table 1. Physical and mineralogical properties 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		

(*) e_{min} and e_{max} obtained from Kolbuszewski [12] method

Triaxial specimens were approximately 70 mm in diameter and 140 mm in height. Samples of Quiou sand were, saturated and then isotropically consolidated under an effective confining stress increasing gradually from 25 kPa to 200 kPa. They were prepared using as wide a range of initial densities as possible (e_0=0.9-1.2) at the end of consolidation phase. To obtain accurate measurements of shear wave velocity at the end of isotropic compression phase, a single sinusoidal wave impulse with an appropriate frequency was adopted for exciting the transmitter element. Travel time was determined by "time domain first arrival method" [14,15] which treats the first zero crossing as the arrival of shear wave (Fig.1). Alternative signal processing procedures have been adopted, namely the cross correlation method, to resolve uncertainties in the interpretation of some measurements.

Liquefaction tests were performed by a NGI (Norwegian Geotechnical Institute) modified simple shear apparatus [16] where cylindrical specimens are about 80 mm in diameter and 20 mm in height, and are laterally confined by a wire-reinforced membrane. Thus, K_0 conditions on the lateral boundary are kept during consolidation and shearing phases. Water-sedimented SS specimens of carbonate sand were prepared at different void ratios and a cyclic shear stress (τ_{cyc}) was then applied on the horizontal plane of the sample in undrained conditions.
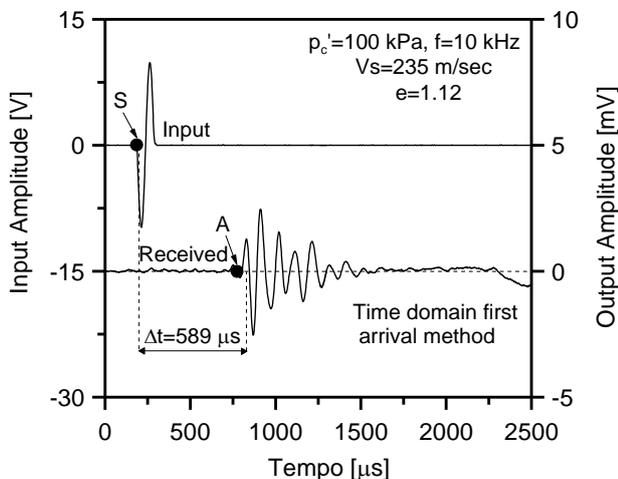

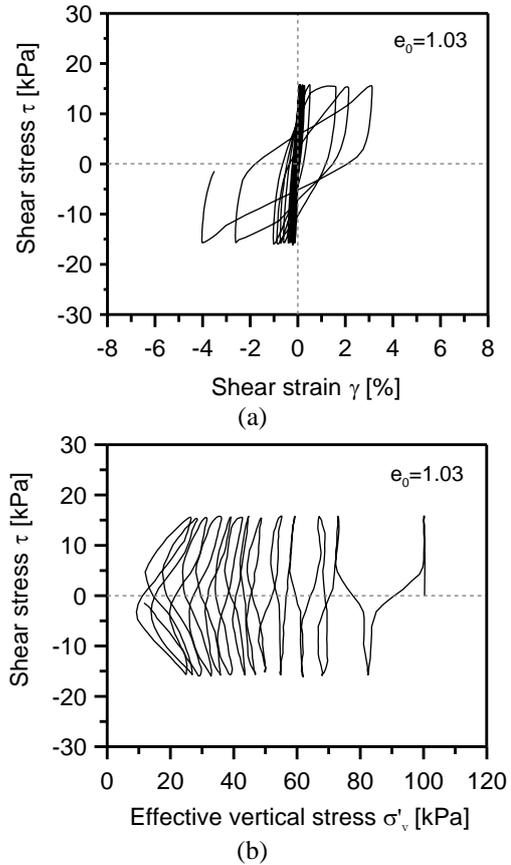*Fig. 1, Typical records of bender element tests on carbonate QS.*

Fig. 2, Typical results of CSS tests performed on carbonate Quiou sand

Undrained cyclic tests were carried out under constant volume conditions by adjusting the vertical load in order to maintain the height of the specimen unchanged during shear [16]. CSS tests were carried out at an initial vertical effective stresses (σ'_{v0}) of 100 kPa.

Figures 2a and 2b present a typical example of CSS test results performed on tested material in terms of stress-strain relationship (τ, γ) and effective stress-path (τ, σ'_v), respectively. In the present research the cyclic resistance ratio, CRR_{SS}, was defined with the achievement of a 3.75% single amplitude shear strain (γ_{SA}), in agreement with Seed et al. [18], practically corresponding to a double amplitude shear strain of 5%.

B. Theoreical considerations on converting laboratory data to field conditions

Some considerations should be included in applying the laboratory test-based CRR-V_{s1} correlations to in situ conditions. Liquefaction resistance under simple shear conditions $CRR_{SS}=\tau_{cyc}/\sigma'_{v0}$ was evaluated under K_0 conditions, thus representing well the in-situ conditions for design purpose compared with cyclic triaxial apparatus adopted in most of the laboratory investigations. It is common to convert CRR_{SS} to in-situ

conditions (i.e. CRR_{field}) in the following way [19]:

$$CRR_{field} = CRR_{SS} \cdot r_c \qquad (1)$$

where it is only necessary to simply multiply CRR_{SS} value by r_c (where r_c=constant accounting for the effect of multidirectional shaking-value of 0.9–1.0).A value of r_c=0.95 was assumed in the present study.

On the other hand, the laboratory measured V_s in BE tests requires adjustment allowing for the different stress state. Accordingly, laboratory V_s can be readily converted as:

$$V_{s,field} = V_s \cdot \left[(1 + 2 \cdot K_0)/3\right]^n \qquad (2)$$

where $V_{s,field}$= equivalent field value of laboratory measured V_s at the depth in question; K_0 of in-situ soils is generally assumed around 0.4 for normally consolidated level ground sites, and n= stress exponent with a value of about 0.25 for silica sands. However, the effect of in-situ K_0 involved in Eq. (2) on the resulting expression for the equivalent field CRR–V_{s1} relationship can be considered negligible for practical purposes, as suggested also by other authors [6].

Finally, it should be noted that in the present study CRR-V_{s1} relationship for carbonate QS was assessed for the reference stress of 100 kPa; the effect of an effective overburden pressure on CRR values in crushable carbonate sands requires specific investigation in order to estimate appropriate overburden correction factors (K_σ).

III. TEST RESULTS

A. Shear wave velocity from bender element tests

For the carbonate sand considered in this study, V_s data are well approximated by the following expression:

$$V_s = C_v \cdot p_a \cdot \left(\frac{p'}{p_a}\right)^n \cdot e^{-d} \qquad (3)$$

Where p' is the mean effective stress, P_a= atmospheric pressure in the same units as the isotropic confining stress=98.1 kPa, "e" is the void ratio and C_v, n_v and d_v are material parameters. For Quiou sand, such parameters resulted C_v=2.54; n and d equal to 0.246 and 0.634, respectively. The variations of V_s with void ratio for different confining stresses, namely 50, 100 and 200 kPa, are shown in Fig. 3. Included, in the same figure are also the trends of V_s gathered from Fioravante et al. [20] from resonant column (RC) performed on specimens of the same carbonate sand, but reconstituted by air pluviation method. It is evident that, for specimens prepared at identical void ratios, the shear-wave velocity of QS is controlled primarily by the effective confining stresses and sample reconstitution method. Water-sedimentation method produced V_s and consequently small strain stiffness (G_0) values which are higher than those
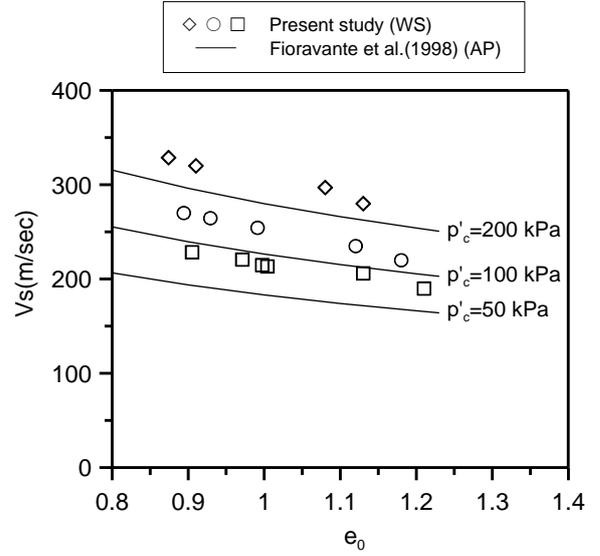

Fig. 3, Influence of void ratio, effective confining stress and reconstitution method on Vs values of carbonate QS

produced by air-pluviation. Effect of sand reconstitution method on shear wave velocity was also found in previous work on silica sands, depending on initial density of tested samples. It is worth mentioning that previous laboratory investigation (from RC and BE tests) suggested that high values of V_s (G_0) can be expected in calcareous sands when compared to corresponding silica sands [21]. Additionally, microstructure can lead to even higher in-situ V_s values since cementation and ageing effects tend to increase the measured in-situ values [22].
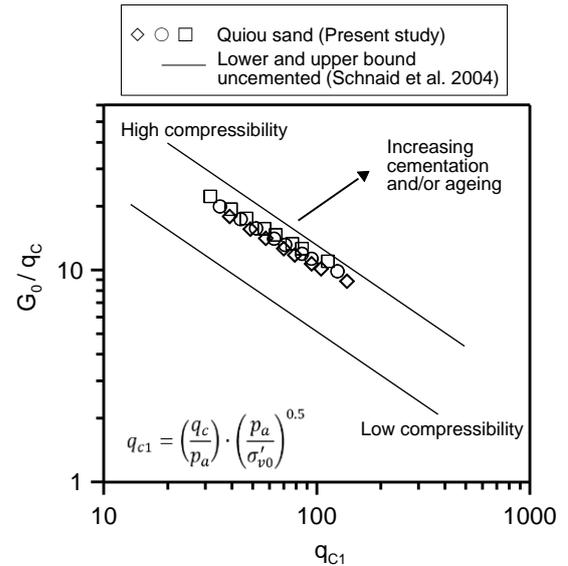

Fig. 4, Correlation between G_0 and q_c for Quiou calcareous sand from laboratory investigation

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It was verified that G_0 data obtained in the present study for uncemented carbonate Quiou sand position well between the upper and lower bounds given in literature for uncemented, unaged sands in terms of ratio of elastic stiffness to cone resistance, G_0/q_c [23], based on interpretation of Static Cone Penetration Tests (CPT) in Calibration Chamber (CC) performed on QS in the context of previous research [24]. (fig. 4).

B. Cyclic liquefaction resistance from simple shear tests

For each initial void ratio, several cyclic simple shear tests were performed at different CSR levels.
In this way test results allowed the development of CSR curves for each relative density. An example of CSR curves obtained for loose specimens of QS is presented in Figure 5. For comparison purposes, selected CSR curves obtained in tests with Ticino silica sand samples with similar grain size features, are also included in the same plot. Liquefaction curves were based on the same failure criterion (γ_{SA}=3.75%. Examination of figure 5 indicates a similar behavior for the two sands tested under the same initial conditions in terms of liquefaction resistance curves. Data reported in literature show comparable or higher liquefaction resistance in calcareous sands as with respect to silica sands, prepared and tested under similar conditions [25,26]. This is partly due to the pronounced grain angularity of carbonate sands. In order to evaluate the cyclic resistance for different values of shear wave velocity, the cyclic resistance needs to be defined for a specific level of shaking (i.e. specific number of cycles to liquefaction).
Therefore, the CRR values shown in Figure 6 were obtained for an equivalent number of 15 cycles to failure to represent a magnitude 7.5 earthquake (Seed and Idriss [3].
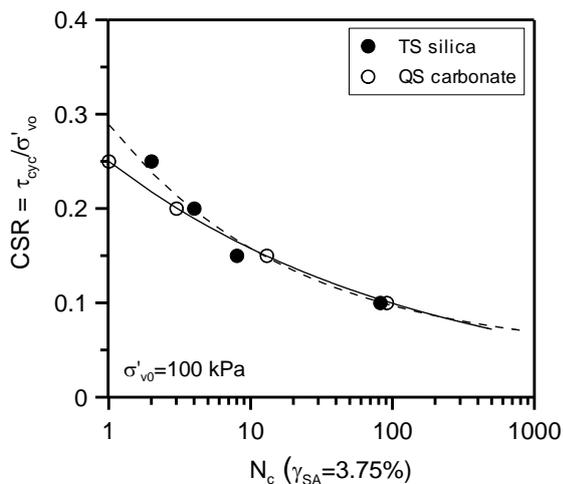

Fig. 5, Cyclic resistance curves of carbonate Quiou sand and silica Ticino sand (loose)
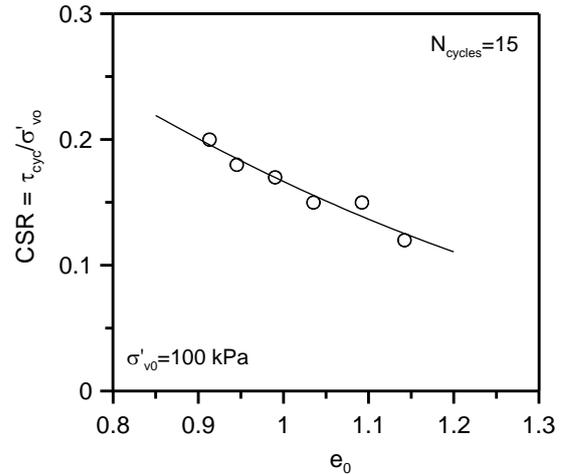

Fig. 6, Cyclic resistance ratio vs. void ratio relationship of carbonate Quiou sand

As expected, liquefaction resistance of Quiou sand was found to increase with increasing relative density, as illustrated in Figure 6, where test results are reported in terms of void ratio (e_0) instead of relative density. In fact, D_r is actually a very unreliable parameter, especially for calcareous sands where crushing occurs (with a continuously changing e_{min} and e_{max}) [27].

C. CRR-V_{s1} relationship and comparison with field-based correlations for silica sands

The CRR_{SS} and V_s from laboratory testing were converted to in situ conditions as discussed under heading (II.B) so that a direct comparison with field based correlations developed for uncemented silica sands by Andrus and Stokoe [28] and by Kayen et al. [29] could be made. CRR-V_s relationships are reported in terms of overburden stress-corrected shear wave velocity (V_{s1}), which is calculated according to the expression:

$$V_{s,1field} = V_{s,field} \cdot \left(\frac{p_a}{\sigma_v'}\right)^{0.25} \qquad (4)$$

where: $V_{s1,field}$= overburden stress-corrected shear-wave velocity and σ_v'= initial effective overburden stress (kPa). The final comparison evidences (fig. 7) that all data obtained in the laboratory for carbonate Quiou sand fall to the right of the field-based curves of clean silica sands. Taking into account the small differences in CRR values exhibited by calcareous vs. silica sands, at equal values of density state (Fig. 5), the results reported in Fig. 7 can be mainly attributed to the higher V_s values of calcareous sand. Additional CSS and BE data not published by the authors but obtained in a similar laboratory investigation on air-pluviated reconstituted specimens of two different carbonate sands, namely Dubai sand (biogenic) and Kenya sand (oolitic), are also included in the same plot. For comparison purposes, data relative to Cabo Rojo

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carbonate (biogenic) sand recently reported in literature [30] are also shown in Fig. 7. In particular, Cabo Rojo sand specimens were prepared by using moist-tamping and laboratory investigation consisted in bender element tests and undrained cyclic triaxial tests. The relationship obtained in the present study together with experimental data from other carbonate sands support the evidence that, for such soils, use of the field-based curves adopted for silica sands is unconservative (i.e. the liquefaction resistance of carbonate sands is lower than that suggested by the field-based approach). Lastly ,carbonate sands may exhibit 'unusual' characteristics that may make traditional cyclic liquefaction trigger methods (either SPT, CPT or V_s) unreliable.

IV. CONCLUSIONS

Previous laboratory studies on silica sands have shown that shear wave velocity can be well correlated to liquefaction resistance, because both V_S and liquefaction resistance are influenced by many of the same factors. However, when carbonate sands are considered, sample preparation, test procedure and interpretation need revising to take into account the crushability and the angularity of the grains.
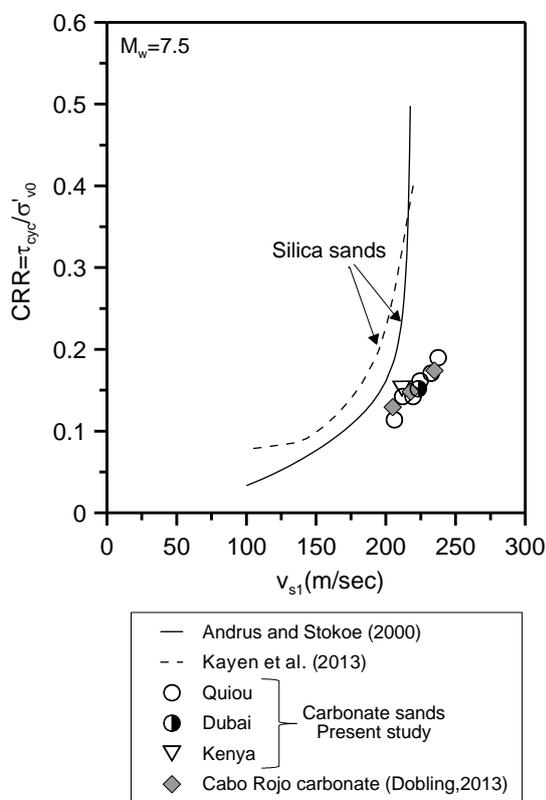
With the aim of establishing a shear wave velocity-based relationship for liquefaction potential assessment, the paper presents the results of bender element tests in conjunction with undrained cyclic SS tests performed on the carbonate (biogenic) Quiou sand. All sand specimens were reconstituted at different void ratios by using water-sedimentation method, in order to better simulate the fabric of natural deposits of marine origin. The results obtained evidenced that data points in the CRR-V_{s1} plot fall to the right of field-based relationships developed for clean silica sands [28,29], and this can be primarily ascribed to the typically higher V_s values exhibited by calcareous sands in comparison to silica sands at the same density state. The results suggest that the currently used shear wave velocity-based liquefaction potential curves are not conservative when applied to carbonate crushable sands. The comparison with further data recently reported in literature, such as on calcareous Cabo Rojo sand tend to strengthen these findings.

Lastly, the authors hope that more laboratory test data will be collected in the future on other carbonate sands in order to develop "soil-specific" reliable correlations for liquefaction evaluation of these soils and to clarify the effect of some factors on the established CRR-V_{s1} correlations, such as: sand reconstitution method, effective overburden stress.

Fig. 7, Comparison of laboratory-based data relative to carbonate sands (σ'_{vo}=100 kPa) with CRR-V_{s1} field-based relationships proposed in literature

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