Liquefaction Susceptibility of Loose Calcareous Sand of Northern Coast in Egypt

La susceptibilité à la liquéfaction du sable calcaire lâche de la côte nord en Égypte

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ABSTRACT: This research studied the liquefaction susceptibility of calcareous sand encountered at the North Coast of Egypt. The study was carried out through a series of cyclic isotropically consolidated undrained triaxial tests, complemented by a suite of physical characterization and index tests. A total of nine (9) cyclic loading tests were conducted on samples prepared at initial relative density of 40%. The variables considered herein included the cyclic stress ratio and initial effective confining stress. The resulting pore-water pressure generation and liquefaction resistance trends for the North Coast calcareous sand were compared to other calcareous and siliceous sands reported in the literature. The test results indicated that the compressible soil skeleton of the North Coast calcareous sand did not result in lower cyclic strength and that the tested sand is less susceptible to liquefaction compared to siliceous sands reported in the literature. This increase in cyclic strength is likely to be the result of the angularity of the calcareous sand particles. Relationship between cyclic resistance ratio and effective confining pressure was developed for the studied relative density.

RÉSUMÉ : Dans cette étude, la susceptibilité à la liquéfaction du sable calcaire rencontré à la Côte Nord de l'Égypte a été investiguée. L'étude a été réalisée à partir d’une série d’essais triaxiaux consolidés non drainés cycliques isotrope, en addition à une série de tests de caractérisation physique et des indices. Neuf (9) essais de chargement cycliques ont été effectués sur des échantillons préparés à un indice de densité relative initiale de 40%. Les variables considérées ici comprennent le rapport de la contrainte cyclique et la contrainte initial de confinement. Les pressions interstitielles et la résistance de liquéfaction résultantes du sable calcaire de la Côte Nord ont été comparées à d'autres sables calcaires et siliceux rapportés dans la littérature. Les résultats des tests ont indiqué que le squelette du sol compressible de la Côte Nord du sable calcaire n'a entraîné aucune réduction de la capacité cyclique et que le sable testé est moins susceptible de se liquéfier par rapport aux sables siliceux rapportés dans la littérature. Cette augmentation de la capacité cyclique est susceptible d'être le résultat de l'angularité des grains de sable calcaire. La relation entre le rapport de résistance cyclique et la contrainte effective de confinement a été développée pour l’indice de densité relative étudié.

KEYWORDS: Loose Calcareous Sand – Cyclic Loading – Triaxial – Liquefaction.

1 BACKGROUND

Calcareous sands result from various biological, mechanical, physical, and chemical depositional environments (Coop and Airey, 2002). As a result, it was found that there are two main reasons behind the difference in their behavior compared to other siliceous sands subjected to similar loading conditions. First, calcareous sand has remarkable intra-particle void space (within the particles), which is mainly caused by the particles being made of shells and corals that include cavities inside their bodies (Hyodo et al., 1998; Coop and Airey, 2002; and Sharma and Ismail, 2006). Second, the angular particle shape of this sand found in various forms such as curved flat particles from fragments of sea shells or hollow tube-shaped particles from remains of skeletons of small marine organisms, which explains the remarkable inter-particle space (between particles). Both reasons lead calcareous sands to be more compressible with higher susceptibility to crushing upon stressing compared to siliceous sands. Different particle breakage factors have been suggested to quantify the particle breakage upon loading; these breakage factors are empirical and depend mainly on changes in particle sizes (Hardin, 1985; and Lade et al., 1996).

Common soil classification systems (such as the Unified Soil Classification System) do not distinguish between calcareous and non-calcareous sands. Classification of calcareous sand/gravel has been proposed by Hallsworth and Knox (1999) to reflect the grain size of particles as well as the composition of carbonates forming the particles. Void ratios in siliceous sands typically vary from 0.43 to 0.85; while for calcareous sands, minimum and maximum void ratios range from 0.54 to 1.62, and maximum void ratios range from 0.71 to 1.98. Specific gravity of minerals composing calcareous soils like calcite is 2.75 and aragonite is 2.95 (Hurlbut, 1971). On the other hand, siliceous minerals are less heavy, since they typically include quartz with a specific gravity value of about 2.65. Specific gravities for calcareous sands typically range from 2.71 to 2.86, while that for siliceous sands can be less than 2.65 (Hyodo et al., 1996; Morioka, 1999; and LaVielle, 2008).

Different approaches have been reported in the literature to evaluate liquefaction susceptibility of soils subjected to cyclic loading, among which studying the number of cycles to failure versus Cyclic Stress Ratio (CSR). CSR is defined as the ratio of the applied cyclic shear stress to the initial effective confining pressure (σ'_c). The effects of CSR and σ'_c on liquefaction susceptibility of siliceous and calcareous sands reported in the literature are presented in this paper. In Egypt, calcareous sand is common along the Northern Coast. This study aims at assessing cyclic behavior of this sand to make a better assessment of the liquefaction susceptibility through a laboratory experimental program.

2 MATERIALS AND EXPERIMENTAL METHODS

The tested calcareous sand was obtained from the near surface of a site located at about km 135 Alexandria – Matrouh road, North Coast, Egypt. The sand has sub-angular to angular grains with light tan to white color. The tested sand has grain sizes mostly ranging from 0.2 to 2 mm with fines content of about 8.75%. The soil is classified as poorly graded sand (SP) according to the USCS (ASTM D2487) and is classified as calcite-sand according to Hallsworth and Knox (1999). The grain-size distribution curve of the tested sand is shown in Figure (1). Maximum and minimum void ratios of the tested sand (ASTM D4253 and D4254, respectively) equaled 1.043 and 0.753, respectively; and the specific gravity (ASTM D854) equaled 2.79.

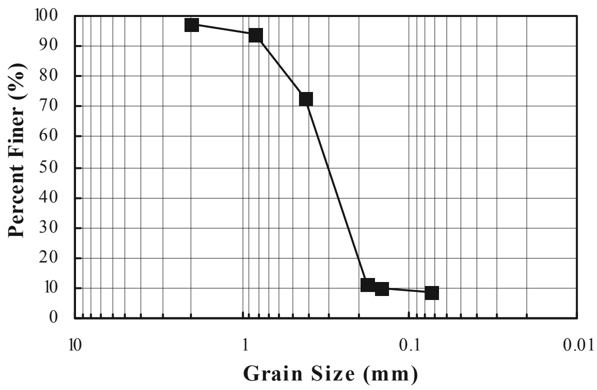

Figure 1. Grain-size distribution curve of North Coast calcareous sand

An electro-pneumatic Cyclic Triaxial apparatus was used to study the liquefaction susceptibility of the tested sand (ASTM D5311). Two isotropically consolidation tests were conducted on two samples prepared at initial relative densities (D_r) of 20% and 75% in the triaxial apparatus to determine the change in the initial D_r under the application of different σ'_c. The relationship between D_r and σ'_c is presented in Figure (2). Using Figure (2) and knowing the test σ'_c and target D_r at end of consolidation stage, the initial D_r at sample preparation was determined. Samples were prepared by tamping using undercompaction technique (Ladd, 1978).

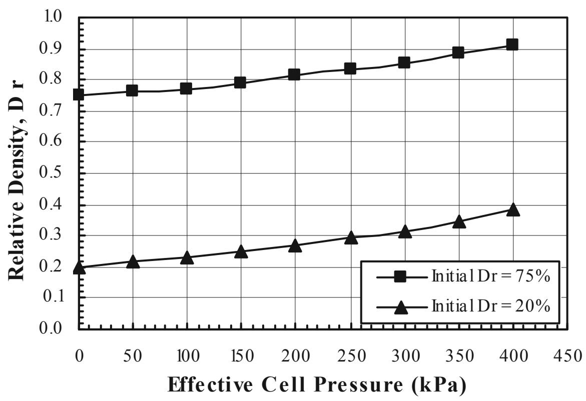

Figure 2. Target relative density contour lines

Typically, sands have high permeability, thus the saturation phase should take place quickly. However, it has been the author's experience that the saturation of calcareous sand was not as easy as the saturation of quartzitic sands, most likely due to the large intra-particle void structure in this type of sand. Thus, flushing the air outside the sample and sample saturation were considered two critical steps prior to cyclic testing. The adopted testing approach used a stair-step procedure for saturation, where the confining cell pressure and back pressure were increased simultaneously every approximately 40 minutes by 50 kPa. Then the sample was left overnight under a back pressure of about 280 kPa. A minimum back pressure of 400 kPa was applied to most samples by the end of the saturation process. Skempton's (1954) pore-pressure parameter "B" of 0.98 was achieved for all test samples. Similar observations for saturation of calcroues sand were reported by LaVielle (2008).

3 CYCLIC TRIAXIAL TESTING

Stress-controlled isotropically consolidated undrained cyclic triaxial tests were conducted on the North Coast calcareous sand to study the liquefaction susceptibility under different σ'_c and Cyclic Stress Ratios (CSR). Each specimen was prepared at a specific initial D_r in order to reach a target D_r of 40% at the end of the consolidation stage. Effective confining pressures of 50, 100, and 200 kPa were applied, then samples were axially loaded at CSR of 0.15, 0.225, and 0.30. Frequency of the cyclic loading was 0.30 Hz and the applied loading function was sinusoidal wave (Agaiby, 2011).

During cyclic loading, excess pore-water pressure (Δu) is generated. The ratio of Δu to the initial σ'_c is defined as the pore pressure ratio, r_u ($r_u = \Delta u/\sigma'_c$). If Δu increases until it reaches σ'_c, the specimen fails as the effective stress drops to zero defining the onset of liquefaction at which $r_u = 1.0$. Sometimes, large strains may occur without reaching zero effective stress. Accordingly, in studying the cyclic behavior of soils, failure criterion is usually defined as the number of cycles required to cause either liquefaction ($r_u = 1.0$) or a specified axial strain (ε) amplitude (ε = 5% according to Ishihara (1993)). For the tested sand, the soil liquefied at relatively low strains (less than 5%).

A typical response of the North Coast calcareous sand at D_r of 40% subject to cyclic loading is presented in Figure (3). The specimen was consolidated under σ'_c of 100 kPa and was axially loaded with a CSR of 0.225. During the first 140 cycles, though the pore-water pressure gradually increased, the axial accumulative strain remained relatively small (nearly 0.5%). Between cycles number 141 and 152, the pore-water pressure increased significantly until it reached the value of the initial σ'_c (i.e., r_u = 1.0), thus reaching liquefaction. This liquefaction failure is typical for contractive calcareous and siliceous loose sands (LaVielle, 2008; and Hussein, 2008).

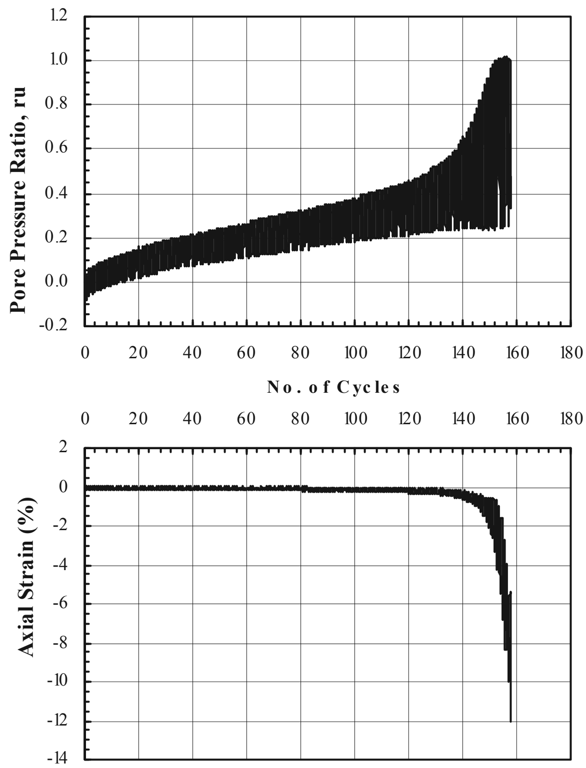

Figure 3. Typical behavior of North Coast calcareous sand subjected to cyclic loading

Hardin's method (1985) was used to quantify the crushing of the tested sand in cyclic triaxial tests. Hardin (1985) based his measurements on the changes in the grain-size distribution curve before and after test. He defined the relative breakage factor (B_r) as (B_t/B_p), where the breakage potential (B_p) is the area between the original grain-size distribution curve and the No. 200 sieve size; and the total breakage (B_t) is the area between the original grain-size distribution curve and the final grain-size distribution curve. For the North Coast calcareous sand tested under cyclic loading at σ'_c ranging from 50 to 200 kPa, the calculated values of B_r ranged from 0.01 (1.09%) to 0.02 (2.23%), which are considered low breakage factors. It was concluded that crushing during testing this sand under cyclic loading was insignificant for the range of σ'_c applied herein.

3.1 *Effect of cyclic stress ratio (CSR)*

The effect of CSR on liquefaction susceptibility was investigated by plotting the number of cycles required to cause liquefaction (r_u= 1.0) versus CSR for samples tested at various σ'_c for D_r of 40% as shown in Figure (4). Results indicated that at the same σ'_c, the number of stress cycles required to reach liquefaction (r_u= 1.0) decreases as CSR increases.

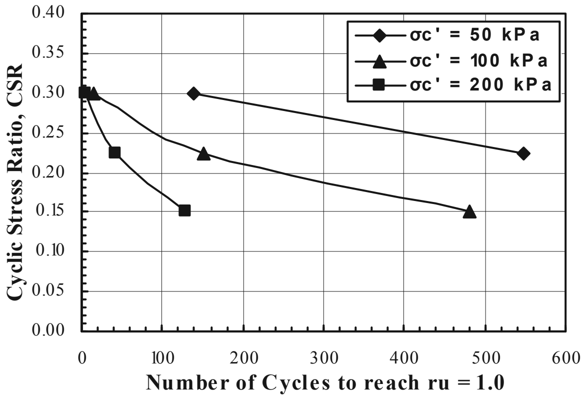

Figure 4. Number of cycles to liquefaction (r_u= 1.0) versus CSR at various σ'_c for North Coast calcareous sand (D_r = 40%)

The effect of CSR on the cyclic resistance of North Coast calcareous sand is in agreement with that attained in previous researches on clean siliceous sands (Seed and Lee, 1966; and Hussein, 2008). Similar agreement in behavior was observed with other calcareous sands reported in literature (Hyodo et al., 1998; Sharma and Ismail, 2006; and LaVielle, 2008).

3.2 *Effect of effective confining pressure (σ'_c)*

The effect of σ'_c on liquefaction susceptibility of the tested sand is illustrated in Figure (5). Number of cycles required to cause liquefaction is plotted versus σ'_c, at various values of CSR. For the same CSR, the number of cycles required to cause liquefaction increased as σ'_c decreased.

Various opinions have been reported in the literature regarding the effect of σ'_c on liquefaction susceptibility for calcareous and siliceous sands. Stedman (1997) observed that in cyclic loading of siliceous sands, increasing the σ'_c generally decreased the resistance to liquefaction (similar to North Coast calcareous sand); however, in the loosest states the increase in confining stress had little effect on resistance to liquefaction. For Dogs Bay carbonate sands, Hyodo et al. (1998) noticed that the cyclic strength increased as σ'_c decreased, which is similar to the behavior of North Coast calcareous sand. Moreover, Finn et al. (1971) mentioned that at a certain void ratio, the CSR and number of stress cycles to reach liquefaction in siliceous sands are uniquely related, independent of the consolidation stress. However, the behavior of North Coast calcareous sand contradicts with what has been reported by Seed and Lee (1966) and Peacock and Seed (1968) for clean siliceous sand, as they found that as σ'_c increased, the number of cycles to failure increased.

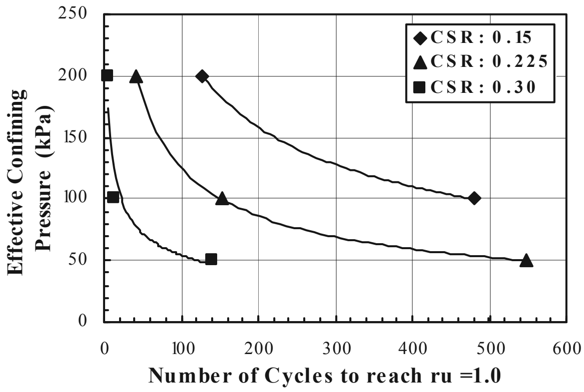

Figure 5. Number of cycles to liquefaction (r_u =1.0) versus σ'_c at various CSR for North Coast calcareous sand (D_r = 40%)

3.3 *Correlation between CRR and other factors*

In this study, the Cyclic Resistance Ratio (CRR) is defined as the CSR required to cause liquefaction in 20 loading cycles to represent an earthquake of magnitude 7.5 (Ishihara, 1993). For tested specimens, the value of CRR at each σ'_c was determined. Variation of CRR with σ'_c is shown in Figure (6).

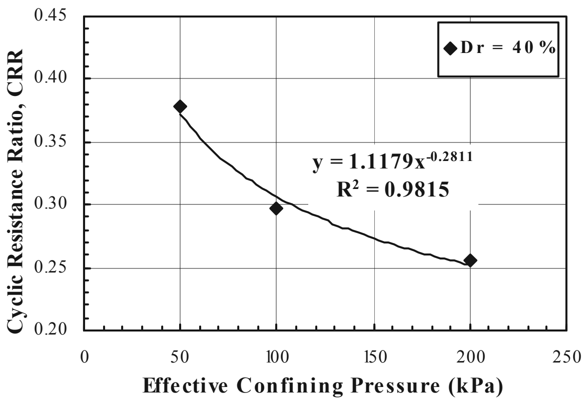

Figure 6. Variation of CRR with σ'_c for North Coast calcareous sand

4 COMPARISON WITH SANDS IN LITERATURE

4.1 *Comparison with siliceous sands*

The obtained test results were compared to other results reported in the literature for the more commonly studied siliceous sands. Generally, the cyclic behavior of the North Coast calcareous sand followed the behavior adopted by siliceous sands. Under the same σ'_c and initial D_r, the number of cycles required to reach liquefaction (r_u = 1.0) increased as the value of CSR decreased as shown in Figure (7).

It was initially thought that the more compressible soil skeleton of calcareous sand would result in a more contractive soil matrix and thus result in calcareous sands being more susceptible to liquefaction than siliceous sands. This research and others have found that this is not true. The results shown in Figure (7) indicate that North Coast calcareous sand has greater cyclic strength and is less susceptible to liquefaction compared to siliceous sands at the same D_r. Increased cyclic strength is likely to be the result of the angular calcareous sand particle shape, which provides more stable interlocking soil fabric resistant to liquefaction (Kaggwa and Poulos, 1990; Hyodo et al., 1996; Hyodo et al., 1998; Morioka and Nicholson, 2000; Sharma and Ismail, 2006; and LaVielle, 2008).

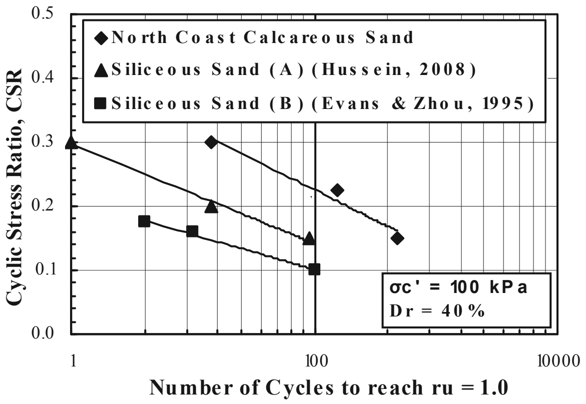

Figure 7. Comparison between North Coast calcareous sand and siliceous sand prepared at D_r = 40% and tested under σ'_c = 100 kPa

4.2 *Comparison with calcareous sands*

Calcareous sands reported in literature generally followed similar trends regarding the behavior under cyclic undrained triaxial loading. The cyclic behavior of North Coast calcareous sand is compared to Playa Santa Calcareous sand in Figure (8).

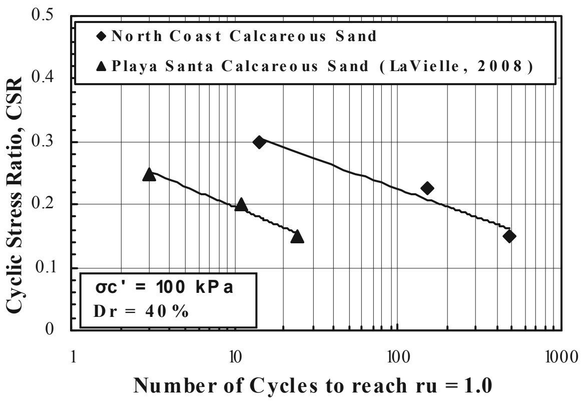

Figure 8. Comparison between North Coast calcareous sand and Playa Santa calcareous sand prepared at D_r = 40% and tested under σ'_c = 100 kPa

5 CONCLUSIONS

1) Failure under cyclic loading for the North Coast calcareous sand prepared at relative density of 40% is governed by the gradual development of excess pore-water pressure until liquefaction is reached.
2) For the same σ'_c, the number of cycles to reach liquefaction decreased as the CSR increased.
3) For the same CSR, the number of cycles to reach liquefaction decreased as the σ'_c increased.
4) The North Coast calcareous sand is less susceptible to liquefaction compared to siliceous sands subjected to similar loading conditions.
5) For the North Coast calcareous sand, the effect of angularity and irregular particle shape on cyclic resistance was found to be more dominant than crushability for the range of tested σ'_c.
6) A soil-specific correlation relating the CRR and σ'_c is developed for the tested sand prepared at relative density of 40%.

6 ACKNOWLEDGEMENTS

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