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Static and cyclic behavior of North Coast calcareous sand in Egypt

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ABSTRACT

This research studies the behavior of calcareous sand located in the North Coast of Egypt, Dabaa area, under static and cyclic loading. The study is performed through a series of monotonic and cyclic undrained triaxial tests conducted on two relative densities and different effective confining pressures. The cyclic tests were carried out at different cyclic stress ratios. Failure under cyclic loading was found to be governed by the gradual development of excess pore water pressure until liquefaction is reached, rather than cumulative development of axial strain (cyclic mobility). The cyclic strength of the tested sand is compared with other calcareous and siliceous sands reported in the literature. The test results indicate that loose Dabaa calcareous sand has higher cyclic strength compared to other siliceous sands, probably due to the existence of different shapes of calcareous sand particles within the tested soil. Relationship between cyclic resistance ratio, effective confining pressure, and relative density was developed for the tested sand.

1. Background

Calcareous sands are the result of various biological, mechanical, physical, and chemical depositional environments [1,2]. There are two main reasons behind the difference in their properties and behavior compared to other siliceous sands subjected to similar loading conditions. First, calcareous sands have remarkable intra-particle void space (within the particles), which is mainly caused by the particles being made of shells and corals that include cavities and voids inside their bodies or on their surfaces [2–7]. Second, the irregular particle shape of this sand, which can be found in various forms such as curved flat particles coming from fragments of sea shells or hollow tube-shaped particles coming from the remains of skeletons of small marine organisms resulting in remarkable inter-particle space (between particles). Both reasons lead to higher possible compressibility of calcareous sands associated with crushing of calcareous grains when sheared. Different particle breakage factors have been suggested in attempts to quantify the amount of particle breakage upon loading; these breakage factors are empirical and depend mainly on changes in particle sizes [8,9].

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 [10] to reflect the grain size of the particles as well as the composition of carbonates forming the particles. Typically for sands, minimum void ratios vary from 0.2 to 0.5, and maximum void ratios vary from 0.8 to 1.2 [11]. Higher void ratios have been reported for calcareous sands. Cataño [12] presented minimum and maximum void ratios for thirteen (13) calcareous sands, where minimum void ratios ranged from 0.5 to 1.6, and maximum void ratios ranged from 1.1 to 2.0. Soil specific gravity is strongly dependant on the mineralogy of the soil particles. The specific gravity of minerals composing calcareous soils like calcite is 2.75 and aragonite is 2.95 [13]. Siliceous minerals, on the other hand, 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 [4,5,12,14,15].

The state of phase transformation is important while studying undrained behavior of sands. Phase transformation is a concept developed by Ishihara et al. [16] that refers to a transient state at which the behavior of soil changes from contractive to dilative; the pore water pressures begin to decrease at this point (phase transformation point, PT) as the deviator stress increases. LaVille [15] mentioned that the typical behavior of calcareous crushable sand during undrained shearing is to adopt an initial contractive tendency followed by a tendency for dilation. Hyodo et al. [6] found that at low confining pressures, calcareous sands may dilate without exhibiting the initial contractive behavior observed at higher confining pressures. With the increase of effective confining pressure (σ'_c), both loose and dense calcareous specimens adopted an initial contractive behavior followed by a tendency for dilation. Thus, as σ'_c increases, both loose and dense sands tend to be more contractive. In $p'-q$ space, where $p'=(\sigma'_1+\sigma'_3)/2$ and

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$q=(\sigma'_1-\sigma'_3)/2$ according to MIT stress path convention, the line drawn through the PT point from the origin is known as the phase transformation line [16]. Hyodo et al. [6] compared the phase transformation stress ratio q/p' for loose and dense Shirasu crushable sands and for dense and medium dense Dogs Bay carbonate sands and found that this ratio is independent of relative density and is constant for a given soil. The previous finding was assured by LaVielle [15].

Different methods have been used to evaluate the liquefaction susceptibility of soil subjected to cyclic loading, among which studying the number of cycles to failure versus Cyclic Stress Ratio (CSR) defined as the ratio of the applied cyclic shear stress to the initial σ'_c. Researchers have investigated the effects of relative density (D_r), σ'_c, and soil type on the number of cycles–CSR relationship. Failure is commonly defined as liquefaction, which corresponds to the number of cycles at which the pore water pressure ratio (r_u) equals 1, where the pore water pressure ratio is defined as the ratio of excess pore water pressure to initial effective confining pressure ($r_u=\Delta u/\sigma'_c$). Sometimes, large strains may occur without reaching r_u of 1.0. 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 ($\varepsilon=5\%$ in double amplitude [17]).

Compared to siliceous sands, particle crushing and rearrangement mechanisms are more significant in calcareous sands, which make calcareous sands more compressible than siliceous sands [2]. Of particular note is how these mechanisms affect the pore water pressure generation during undrained monotonic and cyclic loading and understanding the potential for liquefaction during an earthquake. This study aims at assessing the monotonic and cyclic behavior of Dabaa calcareous sand through a laboratory experimental program.

2. Physical properties of tested material

The tested calcareous sand was obtained from the near surface of a site located at about km 135 Alex-Matrouh road, Dabaa area, North Coast, Egypt. The collected soil consists of irregular-shaped grains with light tan to white color. The tested sand has a fairly uniform gradation (medium sand), with grain sizes mostly ranging from 0.2 to 2 mm, and fines content of about 8.75%. The soil is classified as poorly graded sand (SP-SM) according to the Unified Soil Classification System (ASTM D2488); and is classified as calcite-sand according to Hallsworth and Knox [10]. The grain size distribution curve of the tested sand is plotted with other calcareous sands reported in the literature in Fig. 1.

Maximum and minimum void ratios for the Dabaa calcareous sand (ASTM D4253 and D4254, respectively) are 1.043 and 0.753, respectively. The specific gravity (ASTM D854) of the tested sand is 2.79. Index properties of Dabaa calcareous sand are compared to other calcareous sands reported in the literature in Table 1. Standard and modified proctor compaction tests were conducted on the Dabaa calcareous sand according to ASTM D698 and ASTM D1557, respectively. The results of both tests are plotted in Fig. 2.

X-Ray Diffraction analysis revealed that the sample is composed of a major constituent of Calcite and Aragonite and a trace constituent of Quartz. The mineralogy and geochemistry analysis of the carbonate sample indicated the presence of several minerals in the sand sample with different percentages illustrated in Table 2. A thin section was prepared for microscopic investigation and images of the prepared section under microscopic

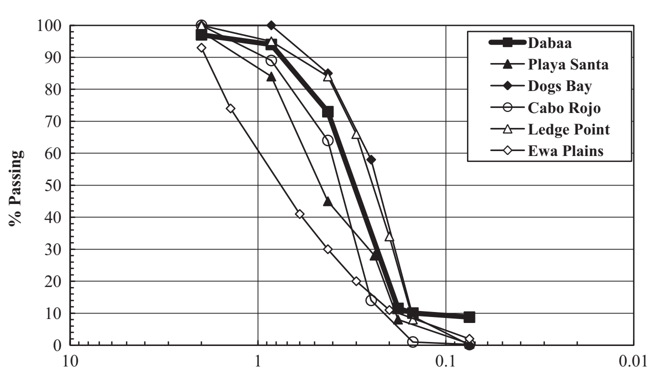

Fig. 1. Grain size distribution curves of Dabaa calcareous sand versus other calcareous sands reported in the literature [6,7,12,14,15].

Table 1
Index properties of Dabaa calcareous sand versus other calcareous sands reported in the literature [6,12,14,15].

Sand	G_s [a]	D_{10} (mm) [b]	C_u [c]	e_{min} [d]	e_{max} [e]
North coast	2.79	0.15	2.40	0.75	1.04
Cabo Rojo	2.86	0.20	1.05	1.34	1.71
Playa Santa	2.75	0.16	2.75	0.80	1.22
Dogs Bay	2.75	0.24	2.06	0.98	1.83
Ewa Plains	2.72	0.20	5.05	0.66	1.30

[a] Specific gravity.
[b] Effective grain size.
[c] Uniformity coefficient.
[d] Minimum void ratio.
[e] Maximum void ratio.

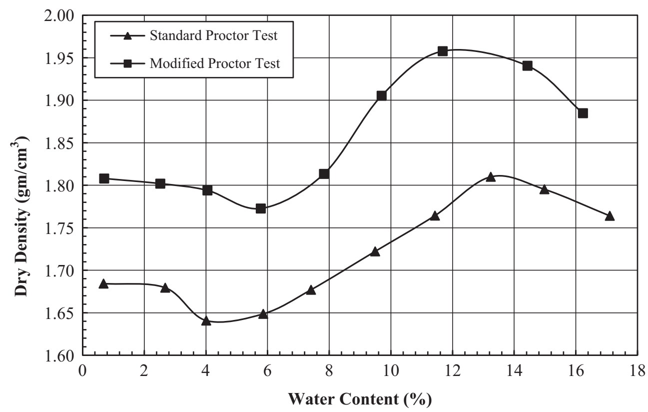

Fig. 2. Standard and modified Proctor compaction curves.

Table 2
Elemental content and mineral composition of Dabaa calcareous sand.

Mineral	Percentage (%)
SiO_2	0.28
TiO_2	0.02
Al_2O_3	0.12
Fe_2O_3	0.02
MnO	< 0.01
MgO	0.2
CaO	55.4
Na_2O	< 0.01
K_2O	0.02
P_2O_5	0.06
SO_3	0.12
Cl	< 0.01
L.O.I. [a]	43.53

[a] L.O.I: loss on Ignition.