Soil Dynamics and Earthquake Engineering 107 (2018) 339–349

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Strain-dependent dynamic properties of Bushehr siliceous-carbonate sand: Experimental and comparative study

Yaser Jafarian[a,*], Hamed Javdanian[b], Abdolhosein Haddad[c]

[a] Geotechnical Engineering Research Center, International Institute of Earthquake Engineering and Seismology, P.O. Box 19395-3913, Tehran, Iran
[b] Department of Civil Engineering, Shahrekord University, Shahrekord, Iran
[c] Department of Civil Engineering, Semnan University, Semnan, Iran

ARTICLE INFO

Keywords:
Sand
Siliceous
Carbonate
Shear modulus
Damping ratio
Stress anisotropy
Hyperbolic model

ABSTRACT

Mixtures of calcareous and siliceous sediments are found in extensive areas of the earth including the seismic-prone regions. However, a few experimental studies on dynamic properties of such soils have been conducted, compared with the siliceous soils. The investigations presented in this paper include: (1) experimental study on shear modulus (G) and damping ratio (D) of Bushehr siliceous-carbonate sand under various stress-density states, (2) comparison of the results with the available models of siliceous sands, and (3) development of a modified-hyperbolic model for the studied siliceous-carbonate sand. Cyclic triaxial and resonant column tests were conducted on reconstituted samples of the Bushehr sands, retrieved from the northern coast of the Persian Gulf. The results indicate that dynamic properties of the sand are less affected by the initial stress anisotropy compared with the initial mean confining pressure (σ'_m) and relative density (D_r). The effect of D_r and stress anisotropy on the shear modulus is more pronounced in higher values of σ'_m. Noticeable discrepancy has been observed between the experimental results of the Bushehr siliceous-carbonate sand and the previous models basically developed for the siliceous sands. Modified hyperbolic models are presented as the shear modulus and damping curves (i.e., G/G_{max}-γ and D-γ) of the tested sand. The hyperbolic models presented in this study can be used for site response analysis of the regions with similar siliceous-carbonate deposits.

1. Introduction

Calcareous sediments are found in temperate and tropical regions and cover vast areas of the earth [1]. This type of soil is typically observed near offshore hydrocarbon industries, such as the Persian Gulf [2]. Carbonate sands originate from reworked shell fragments, skeletal debris of marine organism, and biological depositional environments. Hence, mineralogy, formation process, and grains shape of carbonate sediments may result in noticeable differences in dynamic behavior of such soils and those observed in siliceous soils. In coastal areas, calcareous soils might be found in combination with the lithogenous silicate particles. Shear modulus and damping ratio of siliceous soils have extensively been investigated through experimental studies (e.g., [3–8]), field seismic records (e.g., [9–12]), physical model tests (e.g., [13,14]), numerical simulation (e.g., [15]), and statistical approaches (e.g., [16–18]). However, investigations on dynamic properties of calcareous soils and also soils with a calcareous fraction are rarely found in the literature.

Field and laboratory investigations have highlighted the engineering aspects of calcareous soils in terms of compressibility, volume changes, grains crushing, yielding, friction, and permeability [19–22]. Foundation problems associated with carbonate soil deposits have led to significant research focused on the behavior of these soils [23–28]. Serious problems during pile driving project in the Lavan Petroleum platform in the Persian Gulf, Iran, are an example of engineering problems encountered when dealing with carbonate deposits [29]. Shahnazari and Rezvani [30] studied the monotonic behavior of the Bushehr and Hormuz carbonate sands deposited in the Persian Gulf.

Brandes [31] compared the cyclic simple shear behavior of carbonate sand of the Hawaiian Islands with the Nevada and Ottawa quartz sands. It was concluded that cyclic strength of carbonate sand is generally higher than that of the quartz sand, which is resulting from mineralogical and textural differences. Moreover, some other laboratory studies indicated that cyclic strength of loose carbonate sands is higher than that of quartz sands at equivalent stress conditions [32,33]. Experimental studies of Sharma and Fahey [34] and Coop [35] have shown that cyclic behavior of calcareous soils is different from that of terrigenous non-calcareous soils. Salem et al. [36] studied the behavior of a calcareous sand located on the North Coast of Egypt through a series of undrained monotonic and cyclic triaxial tests. They found that

* Corresponding author.
E-mail addresses: yjafarianm@iiees.ac.ir (Y. Jafarian), javdanian@eng.sku.ac.ir (H. Javdanian), ahadad@semnan.ac.ir (A. Haddad).

https://doi.org/10.1016/j.soildyn.2018.01.033
Received 26 September 2016; Received in revised form 30 September 2017; Accepted 13 January 2018

Nomenclature

G	shear modulus	ν	Poisson's ratio
D	damping ratio	α	factor of initial shear stress
G_{max}	small-strain shear modulus	ρ	mass density
G/G_{max}	normalized shear modulus	V_s	shear wave velocity
D_r	relative density after consolidation	a, b, c, d, m, n, r, s, t	model coefficients
σ'_m	effective mean confining pressure	B	Skempton's saturation parameter
σ'_1	vertical effective stress	D_{10}	grain diameter at 10% passing
σ'_3	effective confining pressure	D_{50}	grain diameter at 50% passing
$\Delta\sigma'$	effective deviatoric stress	C_c	coefficient of curvature
$\Delta\sigma_3$	change in confining pressure	C_u	coefficient of uniformity
Δu_c	change in pore water pressure	PI	plasticity index
P_a	atmospheric pressure = 100 kPa	G_s	specific gravity
τ	shear stress	e_{max}	maximum void ratio
τ_s	initial shear stress	e_{min}	minimum void ratio
γ	shear strain	e	void ratio after consolidation
γ_r	reference strain (shear strain at $G/G_{max}=0.5$)	f_r	resonant frequency
γ'_r	reference shear strain in terms of σ'_m	θ	diffraction angle
γ_{tl}	linear threshold shear strain	RC	resonant column test
γ_{tv}	volumetric threshold shear strain	CT	cyclic triaxial
ε	axial strain	SS	simple shear
		$CTSS$	cyclic torsional simple shear
		XRD	X-ray diffraction

loose calcareous sand has higher cyclic strength compared with siliceous sands. Wang [37] investigated the dynamic properties of calcareous sand from Puerto Rico by conducting resonant column tests. Accordingly, the available equations are not applicable for assessing shear modulus reduction of calcareous sand due to the angular shaped particles of the tested soil. Therefore, the available models on the dynamic and cyclic behavior of siliceous sands might be imprecise for non-siliceous sands with a different origin. Moreover, the comparison between dynamic properties of calcareous and siliceous sands and their combinations seems to be very useful for geotechnical practitioners. Another challenging issue of the carbonate deposits which merit further researches on these soils is the high dependency of their behavior to the original and sedimentary environment. The fact that the carbonate sediments originates from different sources, due to their locations, have led to different behavior of these soils [38,39].

This study focuses on dynamic properties of Bushehr siliceous-carbonate sand, located in the south coast of Iran, through the resonant column and the cyclic triaxial experiments. Shear modulus and damping ratio of this sand were measured in various initial density, effective confining pressure, and stress anisotropy. The tests results are interpreted in details. Thereafter, the experimental results are compared with the available ranges and models mostly attributed to the siliceous sands. Finally, modified hyperbolic models are presented for estimating the normalized shear modulus and damping ratio curves of the studied siliceous-carbonate sand.

2. Experimental procedure

2.1. The siliceous-carbonate sand

The soil tested in this research was obtained from Bushehr Port, a seismic region in the south of Iran. This port is one of the most important and strategic ports located on the northern coast of the Persian Gulf. The Bushehr region has experienced many earthquakes over the last decade due to active faults. On the seismicity importance of the region, Berberian and Tchalenko [40] presented a compilation of field and bibliographical information on earthquakes which occurred within a radius of about 200 km from Bushehr, as part of a general seismicity analysis of Zagros Active Folded Belt. Based on the seismic zonation provided in the Iranian code of practice for seismic resistant design of buildings, Standard No. 2800, the Bushehr region is located in high relative seismic hazard zone with a design bedrock acceleration of 0.3 g for a 475-year return period and a 50th percentile confidence level [41].

Reconstituted specimens of the sand were prepared using bulk samples taken from borrow pits near the coast of the Persian Gulf. The predominant minerals in the soil are distinguishable by X-ray diffraction (XRD) test, which is a mature x-ray technology widely used for mineral identification and quantification. The result of XRD test on the Bushehr sand is shown in Fig. 1, revealing that the most predominant chemical components within this soil are the calcium carbonate ($CaCO_3$) and quartz (SiO_2), respectively. Moreover, calcium carbonate ($CaCO_3$) content of this sand was determined based on the chemical tests recommended by ASTM D4373. The result showed that the Bushehr sand contains 53.1% calcium carbonate. Thus, Bushehr sand is a siliceous-carbonate sand [42].

The grains size distribution curve of the tested siliceous-carbonate sand was embedded in Fig. 1. The soil is classified as poorly graded sand (SP) according to the USCS (ASTM D2487). The maximum and minimum void ratios and specific gravity of the sand were measured according to ASTM D4253, ASTM D4254, and ASTM D854, respectively. Table 1 and Fig. 2a-b present some physical properties and the Scanning Electron Microscopic (SEM) images of the Bushehr siliceous-carbonate sand, respectively. It was pointed out from the microscopic

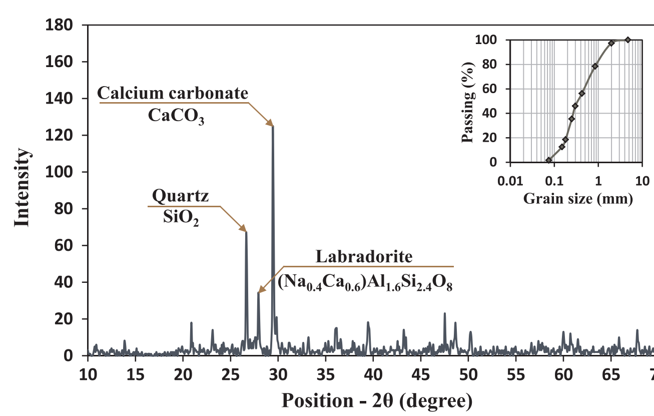

Fig. 1. X-ray diffractogram of Bushehr sand, grains size distribution curve of the Bushehr sand is also embedded in the plot.