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Dynamic properties of calcareous and siliceous sands under isotropic and anisotropic stress conditions

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Abstract

The strain-dependent dynamic properties of sand are generally described by their relative density and mean effective stress, while the contribution of other factors, like soil origin, mineralogy, grain morphology, and initial stress anisotropy, have not been fully recognized. This paper presents the results of an experimental study on the shear modulus and damping ratio of calcareous and siliceous sands of different origins and their identical grain size distribution and stress-density states. Resonant column and cyclic triaxial tests were conducted on reconstituted samples of these two sands obtained from coastal areas. The significance of the initial effective confining pressure and stress anisotropy on the dynamic properties of the sands is evaluated and compared. It is demonstrated that the small-strain shear modulus of the calcareous sand is more affected by an increase in mean effective confining pressure than the siliceous sand. However, the effect of the initial shear on the secant shear modulus of the sands is unique. Based on the test data, a rigorous correction factor is proposed to account for the influence of the initial stress anisotropy on the small-strain shear modulus of the sands. A comparison between the strain-dependent dynamic properties of the calcareous and siliceous sands reveals that the calcareous sand has a higher secant shear modulus, lower damping ratio, and higher linear and volumetric threshold strain. Since the stress-density states and grain size distribution of the two sands were identical in the experiments, the discrepancy in the dynamic properties can be attributed to other factors, including sand origin, grain angularity, mineralogy, and formation processes, which are not commonly taken into account in the current practice.

Keywords: Calcareous sand; Siliceous sand; Shear modulus; Damping ratio; Stress anisotropy

1. Introduction

The shear modulus and damping ratio of siliceous soils have been extensively investigated by geotechnical researchers using experimental (e.g., Hardin and Drnevich, 1972a, 1972b; Seed et al., 1986; Yasuda and Matsumoto, 1993; Lanzo et al., 1997; Rollins et al., 1998; Stokoe et al., 1999; Lin et al., 2000; Zhang et al., 2005; Wichtmann and Triantafyllidis, 2009; Senetakis et al., 2015) and statistical (e.g., Vardanega and Bolton, 2013; Jafarian et al., 2014a, 2015) approaches. In contrast, experimental studies on the dynamic properties of biological soils, such as calcareous sediments, have been very limited. Such sediments are found in temperate and tropical areas and cover approximately 40% of the ocean surface (Holmes, 1978). This type of soil is typically observed around offshore hydrocarbon industries, such as in the Per-

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sian Gulf (Jafarian et al., 2015). Calcareous sands are created by the accumulation of pieces of carbonate materials and usually originate from the reworked shell fragments and skeletal debris of marine organisms. Foundation problems associated with calcareous soil deposits, particularly as experienced by offshore hydrocarbon industries (McClelland, 1988), have led to significant research in an effort to understand the behavior of these soils (e.g., Mao and Fahey, 2003; Coop et al., 2004; Sharma and Ismail, 2006; Hassanlourad et al., 2008; Shahnazari et al., 2016).

Shahnazari and Rezvani (2013) studied the effect of confining pressure, relative density, axial strain, drainage conditions, and grain size distribution on the particle breakage of a calcareous sand from the Persian Gulf. Brandes (2011) found that the cyclic strength of calcareous sands is generally higher than that of quartz sands due to the mineralogical and textural differences. Moreover, other researchers (Nicholson, 2006; Salem et al., 2013) have reported higher cyclic strength for calcareous sands at equivalent stress conditions. Salem et al. (2013) indicated that the non-uniformity of the particle shape may result in the higher cyclic strength of calcareous sands compared with siliceous sands. This finding is in agreement with some other experimental and numerical studies reporting the considerable effect of grain shapes on soil behavior (Guo and Stolle, 2006; Cavarretta et al., 2010; Shin and Santamarina, 2013). The wide variability of the origins of calcareous soils, including their location and the related fauna that make their formation, merit more research to explore the mechanical behavior of these soils.

The dynamic behavior of soils might be profoundly affected by the in-situ stress state acting on the soil elements. Nevertheless, the majority of researchers have focused on isotropically consolidated samples even though the actual in-situ stress state in the field is mainly anisotropic. Some researchers have investigated the effect of the initial stress anisotropy on the behavior of soils (e.g., Yimsiri and Soga, 2002; Ezaoui and Di-Benedetto, 2009; Sivathayalan and Ha, 2011; Jafarian et al., 2013; Gu et al., 2017). Hoque and Tatsuoka (2004) found that the small-strain Young's modulus of soil in a given direction, E_i, generally depends on the principal stress component in that direction, σ_i. The results of piezoelectric bender element tests on Macao marine clay indicated that the values of the shear wave velocity (V_s) increase with an increasing stress ratio (σ_1/σ_3) at the same mean effective stress (Hao and Lok, 2008). The results of cyclic torsional tests by Jafarian et al. (2012) showed that the initial shear stress definitely affects the cyclic behavior of Toyoura sand. Chien and Oh (2002) conducted a series of resonant column tests under anisotropic consolidation and found that G_{max} increases with the initial stress ratio. Payan et al. (2016) carried out bender element tests to demonstrate the effects of the stress state on the shear modulus of sands.

A review of the technical literature clearly indicates that soil properties are profoundly affected by the initial stress anisotropy. However, the role of stress anisotropy on the shear modulus and damping of sands has rarely been addressed in previous works. It seems that further experimental studies are needed to target this issue. On the other hand, the majority of the studies on the dynamic properties of sands were conducted on the compounds of silicate minerals. Hence, investigating the dynamic properties of sands with different mineralogy and (isotropic/anisotropic) stress conditions will yield new conclusions. In this paper, the results of resonant column and cyclic triaxial tests conducted on calcareous and siliceous sands are presented in detail. The secant shear modulus (G_s) and damping ratio (D) of Hormuz calcareous and Babolsar siliceous sands were measured and compared under identical stress and density conditions. The experiments were conducted under isotropic and anisotropic stress conditions to examine how the initial stress state affects the dynamic properties of the sands. Based on the results, a new equation is presented that can be used for the estimation of the small-strain shear modulus in an anisotropic stress state. Subsequently, the strain-dependent dynamic properties of the tested calcareous and siliceous sands are compared.

2. Experimental procedure

2.1. Calcareous and siliceous sands

Two types of calcareous and siliceous sands were selected for cyclic and dynamic tests. The calcareous sand was obtained from Hormuz Island, a seismic region in the south of Iran. Hormuz Island is a historic island 30 km southeast of the commercial port of Bandar Abbas, located on the northern coast of the famous Hormuz Strait. The siliceous sand was obtained from Babolsar City, which is a densely populated seismic region on the southern coast of the Caspian Sea in Mazandaran, a northern province of Iran.

The predominant minerals of the soils are distinguishable by the X-ray diffraction (XRD) test, which is a mature X-ray technology widely used for mineral identification and quantification (e.g., Srodon et al., 2001). The results of XRD tests on the Hormuz and Babolsar sands are shown in Fig. 1, revealing that the most predominant chemical components of these soils are calcium carbonate ($CaCO_3$) and quartz (SiO_2), respectively. Photographs of the Hormuz calcareous and Babolsar siliceous sands, shown in Fig. 1, provide the visual difference between the two tested soils.

An identical grain size distribution curve was synthetically obtained for both sands, as presented in Fig. 1. It should be noted that although minor changes were applied to the natural gradations of the sands, the unique grain size distribution curve in Fig. 1 resembles the original particle size distributions. The soils are classified as poorly graded sands (SP) based on the USCS (ASTM D2487). The maximum and minimum unit weights and specific gravity of the sands were measured according to ASTM D4253, ASTM D4254, and ASTM D854, respectively. Table 1 presents