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Effective parameters for the particle breakage of calcareous sands: An experimental study

Habib Shahnazari *, Reza Rezvani

School of Civil Engineering, Iran University of Science and Technology, P.O. Box 16765-163, Narmak, Tehran, Iran

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ABSTRACT

Calcareous sediments have different behavior under monotonic and cyclic loadings compared to that of terrigenous soils. Particle breakage is considered the most important feature of calcareous soils and has been used in many experimental investigations recently. This phenomenon affects some characteristics of carbonate sediments such as compressibility, shearing strength and permeability. In this study, experiments were conducted to evaluate the parameters that affect the particle breakage of calcareous sands, including confining pressure, relative density, axial strain, drainage conditions and grain size distribution. The input energy per unit volume of the soil was also calculated to analyze the effect of this parameter on the particle breakage. In the testing program, two calcareous sands from different locations in the Persian Gulf, namely Bushehr Port (BP) and Hormuz Island (HI) sands, were used for the triaxial compression tests. The experimental results showed that the input energy played an important role in the particle breakage behavior of used soils. In comparison to other parameters considered in this study, axial strain as a representation of the effect of deviatoric loading had major influences on the amount of crushing. The results also indicated that HI sand particles yielded at a higher stress than BP sand.

1. Introduction

Carbonate sediments are located in temperate and tropical areas and cover approximately 40% of the ocean surface (Holmes, 1978). This type of soil is typically observed near offshore hydrocarbon industries, such as the Persian Gulf and near the coasts of Australia. Thus, understanding the mechanical behavior of these sediments belongs in the field of engineering. Previous practical experiences also showed that it is difficult to measure geotechnical parameters and design and construct different geotechnical structures that are associated with the calcareous sediments (Kaggwa, 1988; Kaggwa et al., 1988; King and Lodge, 1988; Airey, 1993; Hasanlourad et al., 2008; Dehnavi et al., 2010; Hassanlourad et al., 2011; Wang et al., 2011). Serious problems during pile driving in the Lavan Petroleum platform in Iran are relevant instances of engineering problems with calcareous deposits (Wang et al., 2011). It has been reported by many researchers that there are some differences between the mechanical behaviors of calcareous and siliceous sands. They have also described some of the inherent differences among various types of calcareous deposits (Datta et al., 1979; Celestino and Mitchell, 1983; Coop, 1990; Brandes, 2011). Particle breakage is the most effective parameter that describes the physical behavior of calcareous sands and, therefore, has been a topic of interest among geotechnical researchers recently.

Particle breakage influences the strength and stress–strain behavior of soils (Hardin, 1985). Hyodo et al. (1999) performed a series of monotonic and cyclic triaxial tests under high confining pressures. They verified that particle breakage had a significant effect on the undrained shearing behavior of sands. Ueng and Chen (2000) modified the Rowe stress-dilation theory in triaxial tests for crushable soils:

$$\frac{\sigma_1'}{\sigma_3'} = \left(1 - \frac{d\varepsilon_v}{d\varepsilon_1}\right)\tan^2\left(45 + \frac{\varphi_u}{2}\right) + \frac{dE_B}{\sigma_3' d\varepsilon_1}(1 + \sin\varphi_u) \quad (1)$$

where σ'_1 is the maximum principal stress, σ'_3 is the minimum principal stress, $d\varepsilon_v$ is the volumetric strain increment (contraction is positive), $d\varepsilon_1$ is the axial strain increment (compression is positive) and φ_u is the internal friction angle between soil grains. The second term on the right side of Eq. (1) corresponds to the particle breakage, and dE_B is the energy consumed related to grain crushing. Luzzani and Coop (2002) and Coop et al. (2004) performed a series of large strain ring shear tests on calcareous Dogs Bay sand. They found that particle breakage continued after reaching the critical state and increased up to very large strains. They believed that the critical state was a balance between volumetric compression due to particle breakage and dilation caused by the rearrangement of the crushable sands. Hasanlourad et al. (2008) and Rezvani et al. (2011) experimentally investigated carbonate sands located in the Persian Gulf to determine the influence of particle

* Corresponding author. Tel.: +98 21 73913128; fax: +98 21 77240398.
E-mail addresses: hshahnazari@iust.ac.ir (H. Shahnazari), r_rezvani@iust.ac.ir (R. Rezvani).

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breakage on the total friction angle. The result showed that the curvature of Mohr–Coulomb envelope in calcareous sands was more than that of terrigenous sands. They concluded the parameter that caused more nonlinearity of Mohr–Coulomb envelope was the high breakage of calcareous soil particles.

Hardin (1985) and Lade et al. (1996) reported that different parameters, such as the particle size distribution, shape of soil particles, effective stress condition, effective stress path, void ratio, particle hardness (including hardness of cementing material or weakest constituent of a particle and weakest particles of an element) and the presence or absence of water, affect the particle breakage of soils.

Several researchers have attempted to quantify the amount of particle breakage of soils. Most of them used particle size distributions to measure the particle breakage. Some of them suggested the amount of increase of passing percent of one size (e.g. D_{50}) in gradation curves (Leslie, 1963, 1975; Marsal, 1965; Lee and Farhoomand, 1967). Morrison et al. (1988) indicated that applying a special sieve size to measure particle breakage is not appropriate. Hardin (1985) proposed a special procedure based on the overall particle size distribution that is known as the "Hardin method". This method has been accepted by many researchers in their studies (Luzzani and Coop, 2002; Coop et al., 2004; Hasanlourad et al., 2008).

In this study, the effects of important parameters, including confining pressure, relative density, drainage conditions, axial strain and grain size distribution on the particle breakage of two different calcareous sands, were assessed. A series of triaxial compression tests was conducted to evaluate the effects of these parameters. The specimens were prepared in different conditions and were tested by a triaxial apparatus under both drained and undrained conditions. Grain size distribution analyses to assess the particle breakage were performed before and after each test, and the breakage values were calculated by the Hardin method. The energy (or work) performed per unit volume of soils was also calculated to evaluate the effect of this important parameter on the particle breakage of calcareous sands.

2. Soil characterization

The carbonate soils, which were studied in this research, were obtained from the northern shores of the Persian Gulf: one soil was from Bushehr Port (BP), and the other was from Hormuz Island (HI). These two places are located on the map (Figure 1).

The grain size distributions of the used soils are shown in Fig. 2. It can be inferred from the gradation curves that the selected soils were well-graded sand (SW). The $CaCO_3$ content of the soil samples was

Fig. 1. Location of Hormuz Island and Bushehr Port in the Persian Gulf.

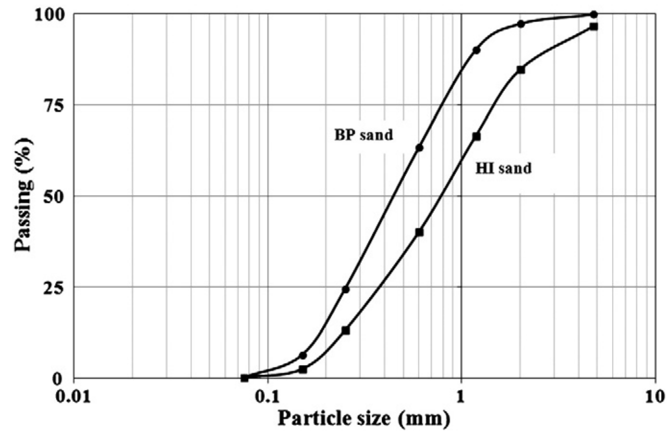

Fig. 2. Grain size distributions of the calcareous sands.

determined based on the British Standard 1377 test (BSI, 1990). The results showed that the HI and BP sands contained 53 and 44% calcium carbonate, respectively. Table 1 demonstrates some physical properties of the carbonate sands.

Figs. 3 and 4 illustrate the microscopic image (SEM) of HI and BP soils. It can be concluded from these microscopic photographs that both types of soils were dominated by thin-walled mollusk and echinoderm plate fragments and thick-walled Foraminifera. As can be seen in these figures, HI sand contained more angular particles than BP sand. The different physical properties of the sands, which can be seen in Table 1, resulted from their different grain origins due to their different locations (Dehnavi et al., 2010; Rezvani et al., 2011).

3. Sample preparation and testing procedures

In this study, the specimens were prepared by the air pluviation method (Bishop and Henkel, 1957; Ladd, 1978). Dry soil spread into a mold with a zero height of fall, which is fixed within the triaxial apparatus and lined with a rubber membrane. To obtain the desired density, tapping energy was applied by hitting the lateral surface of the mold. The size of specimens was approximately 70 mm in diameter and 140 mm in height. To achieve the saturation condition, after flushing CO_2 and exuding de-aired water to the specimens, a back pressure of 200 kPa under an effective pressure of 10 kPa was applied to the samples. A B-value of greater than 0.95 was guaranteed using this method of saturation. After that, samples were isotropically consolidated under the desired pressures. The loading procedure was applied at the strain control condition with a rate of 0.5 mm/min in both drained and undrained conditions.

The specimens were tested by the triaxial apparatus located in the Geotechnical Engineering Research Center (GERC) of the Iran University of Science and Technology (IUST). The data acquisition system included a PC machine and an analogue-to-digital converter (ADC).

At the end of each triaxial test, the grain size distribution was analyzed to measure the amount of particle breakage. In this research, Hardin method was used to assess particle breakage (Hardin, 1985). Hardin (1985) found that the breakage of particles terminated when the gradation curve of soil reached a stable condition. The final condition was achieved when all particles were smaller than 0.074 mm

Table 1
Physical properties of the calcareous sands.

Soil	Grain shape	D_{50} (mm)	C_u	C_c	e_{min}	e_{max}	G_s
HI	Angular	0.78	4.47	0.87	0.625	0.909	2.76
BP	Subangular	0.43	3.2	0.84	0.726	1.051	2.71