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An insight into the mechanical behavior of binary granular soils

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ABSTRACT

This paper investigates the participation of the fines fraction in the load-carrying structure of binary mixtures of granular soils. For this purpose, various fractions of two fine sands were added to two coarse sands with the same particle size distribution, but different particle shape characteristics. Based on the results of 144 direct shear tests, it was found that fines participation in the load-bearing structure increases with fines content. At the same fines content, the participation of the fines in the load-carrying structure of loose mixtures is greater than in samples that were initially compacted. In addition, it was observed that fines participation rises with the increase in the average size of the fines fraction.

Introduction

The mechanical behavior of granular soils (e.g., sands, gravel, sandy gravels, gravelly sands, and non-plastic silty sands) is usually considered complex because they exhibit both solid- and liquid-like behavior depending on their state. Therefore, numerical modeling of the behavior of granular soils is a challenging issue in both continuum and discontinuum contexts. While the mechanical behavior of clean uniformly graded sands and gravels has been reported extensively in the literature (e.g., Been & Jefferies, 1985; Verdugo & Ishihara, 1996; Yoshimine, Ishihara, & Vargas, 1998), the influence of the presence of fines constituents in coarse granular structures has received less attention. However, previous work has revealed that experience gained from studies on clean sands and gravels might not always be relevant to binary mixtures of granular soils. Georgiannou, Burland, and Hight (1990) reported that adding up to 20% kaolin to Ham River sand makes the mixed soil unstable and increases its tendency toward pore pressure buildup and static liquefaction under undrained conditions. Fragaszy, Su, Siddiqi, and Ho (1992) reported that large sub-rounded to rounded smooth soil particles floating in a fine matrix do not significantly affect peak shear strength and deformational behavior of the mixed soil. Kuenza, Towhata, Orense, and Wassan (2004) studied the behavior of gravel–sand mixtures using hollow-cylinder torsion shear tests. They showed that for gravel content of up to 40%, the sand matrix controlled the stress–strain-strength response of the mixture. However, a gradual increase in dilation was reported in gravel contents >40%, whereby the gravel particles controlled the mechanical behavior of the mixture. Seif El Dine, Dupla, Frank, Canou, & Kazan (2010) performed a series of large-sized triaxial tests to study the behavior of gravelly sands. In their study, up to 35% volume of natural gravel with angular particles was added to Fontainebleau sand with sub-rounded grains. They reported an increase in the peak shear strength and internal friction angle at failure, as well as a decrease in dilation with gravel content. Cho et al. (2006) and Wang, Zhang, Tang, & Liang (2013) showed that the shear strength of granular soils is influenced directly by particle size distribution.

Sands containing non-plastic silt are a particular type of binary soil (i.e., mixtures of two uniformly graded non-plastic granular soils), which have received considerable attention in the literature. According to a comprehensive assessment of documented case histories in the literature, Yamamuro and Lade (1999) reported that the majority of liquefaction-induced disastrous events have occurred in natural and man-made deposits of silty sands. Laboratory studies have indicated that for the same global void ratio, the critical state shear strength and the tendency toward dilation decrease with silt content up to a threshold silt content of about 25–40% of the solid weight. Further increase in fines content beyond this approximate limit leads to an increase in the critical state shear strength and dilation (Huang, Huang, Kuo, and Tsai, 2004; Murthy, Loukidis, Carraro, Prezzi, & Salgado, 2007; Papadopoulou & Tika, 2008; Rahman, Lo, & Baki, 2011; Stamatopoulos, 2010; Thevanayagam & Martin,

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Nomenclature

C_c	coefficient of curvature
C_u	coefficient of uniformity
d_{50}	mean size of fine sand
D_{50}	mean size of coarse sand
d_{min}	minimum size of particles in fine sand
D_{min}	minimum size of particles in coarse sand
d_{max}	maximum size of particles in fine sand
D_{max}	maximum size of particles in coarse sand
e	global void ratio (=V_v/V_s)
e_0	initial value of global void ratio
e^*	intergranular void ratio [see Eq. (2)]
e_{max}	maximum void ratio
e_{min}	minimum void ratio
e_{sk}	skeleton void ratio [see Eq. (1)]
FC	fines content
G_s	$=\rho_s/\rho_w$
p'	mean principal effective stress
R	average roundness of particles [see Cho, Dodds, & Santamarina (2006)]
S	average sphericity of particles [see Cho et al. (2006)]
u	shear displacement of sample in direct shear test
v	normal displacement of sample in direct shear test
V_s	total volume of solid phase per unit volume
V_v	total volume of void per unit volume
β	fines participation factor [see Eq. (2)]
ρ	average regularity of particles (=$(R+S)/2$)
ρ_s	average density of solid phase
ρ_w	density of water (=1000 kg/m^3)
σ_n	normal stress in direct shear test
τ	shear stress in direct shear test
χ	particle size ratio (=D_{50}/d_{50})

2002; Thevanayagam, Shenthan, Mohan, & Liang, 2002; Zlatović & Ishihara, 1995).

In all the works cited above, the mechanical behavior of binary granular soils with large values of particle size ratio (e.g., silty sands, gravelly sands, and sandy gravels) was studied. However, the mechanical behavior of binary soils with low particle size ratio, such as mixtures of two uniformly graded sands, is not well understood. In previous work, direct shear tests have been applied by a number of researchers to study the mechanical behavior of granular soils. Tong, Fu, Zhou, & Dafalias (2014) studied the influence of initial anisotropy and particle shape on the shear strength of various sands using modified direct shear apparatus. For well-graded sand–gravel mixtures, Hamidi, Azini, and Masoudi (2012) studied the impact of gradation on the volume change and the shear strength of various mixtures. Simoni and Houlsby (2006) performed an extensive series of direct shear tests on sand–gravel mixtures with gravel contents ranging from 0 to 100%. In the present study, a theoretical classification based on the microstructure of binary soils is reviewed. Then, the mechanical behavior of different binary mixtures of uniformly graded sands with different average particle shapes is studied. Based on the results of the experiments, the participation of the finer fractions in the mechanical behavior of the mixture is estimated.

Microstructure of binary granular soils

Thevanayagam et al. (2002) and Thevanayagam and Martin (2002) suggested a classification system for granular mixtures based on a consideration of contact density. In their system, there are three extreme limiting categories for binary granular mixtures: (a) coarse particles are mainly in contact with each other (see cases (i)–(iii) in Fig. 1), (b) fine particles are primarily in contact with each other (see cases (iv-1) and (iv-2) in Fig. 1), and (c) a layered system, which is not discussed further here because of the lack of homogeneity (see Fig. 1(c)). According to Thevanayagam et al. (2002), coarse particles are in direct contact in case (i) and fine particles only fill the voids between the coarser grains without any active participation in the load-carrying structure. However, fines have partial participation in the soil load-carrying structure in case (ii). In case (iii), coarse particles are separated to some extent by fine particles and hence, fines make a partial contribution to the load-bearing structure of the binary mixture. In cases (iv-1) and (iv-2), coarse particles float within the fine matrix and strong force networks are controlled predominantly by the fines phase.

Based on the above scheme, fine particles could fill large voids between coarse grains without any significant participation in the strong force transmitting network; nonetheless, they contribute to the reduction of the global void ratio. Thus, the presence of fine particles within a coarse matrix leads to a reduction in global void ratio without any increase in the strength of the load-carrying structure of the mixture. Thevanayagam (2007) showed that for case (i) in Fig. 1 (for which $FC \le 0.05$–0.07), the fines phase does not actively participate in the load-carrying structure when $\chi > (1/((4/3)\sin(\pi/3) - 1)) \approx 6.5$, in which the particle size ratio χ is defined by the ratio D_{50}/d_{50} (D_{50} and d_{50} represent the mean

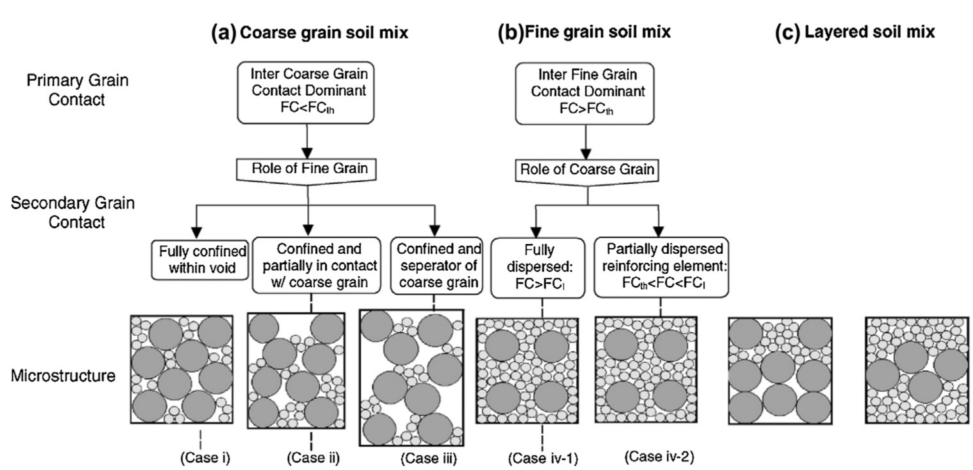

Fig. 1. Microstructure classification of binary granular soils (Thevanayagam et al., 2002).