Soils and Foundations 2015;55(5):1148–1157

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Soils and Foundations

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Experimental characterization of the influence of fines on the stiffness of sand with inherent fabric anisotropy

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Received 7 March 2014; received in revised form 6 May 2015; accepted 22 May 2015
Available online 26 September 2015

Abstract

This paper reports the experimental findings regarding the influence of fines on the stiffness reduction, the stiffness anisotropy, and the stiffness changes (during aging) of Toyoura sand and kaolinite (fines) mixtures. The fines content of the mixture samples ranged from 0% to 30% by weight. A tailor-made true triaxial apparatus was used and equipped with a bender element system to measure the shear modulus and with the I-Scan system to monitor the contact forces within the soil sample. By adding fines, the shear moduli of the samples, i.e., G_{hh} and G_{hv} (or G_{vh}), were reduced, such that the higher the fines content, the higher the reduction and the higher the confining pressure, the smaller the reduction. For a given confining pressure σ', the percentage stiffness anisotropy of the samples increased as the fines content was increased from 0% to 2% and then to 8%. As the fines content was increased from 8% to 15%, the percentage stiffness anisotropy gradually decreased. It ultimately reached a small value at which the fines content was 20% where the fines-controlled soil matrix minimized the stiffness anisotropy induced by the inherent fabric anisotropy of sand particles. The aging rates for G_{hh} and G_{hv} were both enhanced after adding fines, and the enhancement was larger as the fines content was increased because the amount of sample creep also increased. A larger amount of sample creep can lead to a greater degree of contact force homogenization which enhances the soil stiffness. This was evidenced by the change in the associated coefficient of variance (CV) of the contact forces measured by the tactile pressure sensors. The aging rate was always greater in G_{hh} than in G_{hv} regardless of the different fines contents. Yet, such aging rate anisotropy became minor as the fines content reached 15%.

Keywords: Fines effects; Fabric anisotropy; Stiffness anisotropy; Aging; Contact forces

1. Introduction

Natural sandy soils often contain different amounts of fines, i.e., silt and clay. Many studies have clearly demonstrated that fines can influence the engineering properties of sandy soils, such as the strength and dilatancy responses, compression behavior, resultant void ratios of compacted samples, and the associated microstructure. Some of these studies and their findings are briefly summarized as follows. Georgiannou et al. (1990) investigated the stress–strain behavior of clayey sand using undrained triaxial tests. For a given granular void ratio, they found that the undrained brittleness and strain to phase transformation increase as the clay content is increased from 4.6% to 10%. When the clay content exceeds 20%, the trend is reversed. When the clay content reaches 30%, the soil sample is no longer dilatant and exhibits a response like that of a sedimented clay. Salgado et al. (2000) performed a series of

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Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2015.09.015
0038-0806/

triaxial and bender element tests to study the effects of fines (silt) on the small-strain stiffness and stress–strain responses of silty sand samples. They demonstrated that the small-strain stiffness decreases dramatically even if there is only a small percentage of silt in the samples. However, the samples become more dilatant and both the peak and the critical-state friction angles increase once the fines content is increased. Vallejo and Mawby (2000) carried out a series of direct shear tests on mixtures of dry Ottawa sand and dry kaolinite and observed that shear strength depends upon the clay (or granular) content. When the fraction of granular material is larger than 75%, the shear strength of the mixture is similar to that of the granular material. When the granular material content is less than 40%, the shear strength of the mixture is then determined by the clay. They also suggested that the minimum porosity of the mixture represents the theoretical boundary between the sand-controlled and the clay-controlled regimes, and that the associated shear strength is maximized when the mixture is prepared at the minimum porosity. Monkul and Ozden (2007) also performed direct shear tests and they too found that the shear strength of a mixture tends to decrease once the fines content of the mixture exceeds the transition value.

Fines may also affect the compression characteristics of coarse-grained soils. Martins et al. (2001) observed that the presence of fines prevents the yielding of a unique compression line for sandy soils. Hence, they suggested that a new framework is needed to model such soils, which do not exhibit the conventional compression behavior. Monkul and Ozden (2007) conducted oedometer tests on reconstituted kaolinite–sand mixtures. Their experimental results demonstrated that the compression behavior of mixtures is mainly dependent on sand before the fines content reaches a transition value. However, once it exceeds this value, kaolinite determines the associated compression behavior instead. The transition value varies between 19% and 34%, depending on the initial conditions, such as the initial void ratio and the stress conditions of the mixture.

The void ratios of compacted coarse-grained soils have also been found to be a function of the fines content (Vallejo and Mawby, 2000; Yang et al., 2006). The resultant void ratios after a sample has been compacted decrease initially with an increasing fines content, but then increase with the further addition of fines. This transition value for the fines content, once again, marks the boundary between the sand-dominated and the fines-dominated soil matrixes. Lade and Yamamuro (1997) suggested that this transition value is larger than 30%. Lade et al. (1998) also offered an explanation for this behavior, namely, that for a soil with a zero fines content, its structure is formed from large (coarse) particles. However, once fines are added to the soil, the pores formed by those large particles will be filled with fines; and therefore, the overall void ratio will decrease. The minimum void ratio is reached when the voids are completely occupied by fines. After this state of minimum void ratio, as the fines continue to jam into the voids, the large particles in the original structure will be pushed apart. Thus, the void ratios are found to increase with the fines content instead.

Tanaka et al. (2003) reported that the silt or sand content has an important effect on the pore-size distribution of soils. Zhang and Li (2010) investigated the microstructures of coarse-grained soils with various fines contents. They concluded that a soil sample with a fines content above 30% has a fines-determined microstructure, which exhibits dual-porosity (i.e., containing both intra-aggregate and inter-aggregate pores) and is sensitive to changes in water content. For a soil sample with a fines content below 30%, its soil structure is determined by coarse particles and it is stable despite changes in water content.

Most sand particles are not perfectly round and have different degrees of fabric anisotropy, which in turn can give rise to anisotropic engineering properties, for instance, fabric-induced stiffness anisotropy (e.g., Stokoe et al., 1985; Santamarina et al., 2001; Mitchell and Soga, 2005; Wang and Mok, 2008; Wang and Gao, 2013). However, studies on the effect of fines on the fabric-induced stiffness anisotropy of sandy soils are rare and many questions remain unanswered. For example, does the addition of fines increase or decrease the fabric-induced stiffness anisotropy? What is the transition value of the fines content above which the fabric-induced stiffness anisotropy is minimized? And, how do fines alter the enhancement in stiffness during aging? Here, aging refers to the time-dependent property changes in soils subjected to a constant effective stress (Mitchell and Soga, 2005). Finding the answers to these questions would enable us to gain a more complete understanding of the influence of fines on the engineering properties of sandy soils. Therefore, this serves as the main goal of the present experimental work. Experiments were conducted here using a tailor-made true triaxial apparatus equipped with a bender element system and the I-Scan® system (Tekscan Inc., MA., USA). The bender element system was used to characterize the changes in the small-strain shear moduli in three orthogonal directions after different amounts of fines (kaolinite) were added to Toyoura sand samples that have inherent fabric anisotropy. The time (or aging) effects on the modulus changes were examined in particular, and the corresponding measurements from the I-Scan system served as complementary information to assist with the explanation of the experimental findings. The previous findings in Wang and Gao (2013), regarding the behavior of the stiffness anisotropy of dry, clean Toyoura sand, serve as an important reference and guide to assist in the explanations of the experimental results of this study.

2. Experimental details

2.1. Experimental setup

Fig. 1 presents the experimental setup, which consists of a true triaxial apparatus, a bender element system, and the I-Scan system. Details of the true triaxial apparatus and the bender element system can be found in Wang et al. (2006) or Wang and Mok (2008) and are briefly described in this section to