Particuology 21 (2015) 160–172

Contents lists available at ScienceDirect

Particuology

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

A numerical analysis of the shear behavior of granular soil with fines

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ARTICLE INFO

Article history:
Received 28 May 2014
Received in revised form 7 August 2014
Accepted 14 August 2014

Keywords:
Granular soil
Fine particle
Shear behavior
Discrete element method
Fabric anisotropy
Coordination number

ABSTRACT

Shear behavior of granular soil with fines is investigated using the discrete element method (DEM) and particle arrangements and inter-particle contacts during shear are examined. The DEM simulation reveals that fine particles play a vital role in the overall response of granular soil to shearing. The occurrence of liquefaction and temporary reduction of strength is ascribed mainly to the loss of support from the fine particle contacts (S–S) and fine particle-to-large particle contacts (S–L) as a consequence of the removal of fine particles from the load-carrying skeleton. The dilative strain-hardening response following the strain-softening response is associated with the migration of fine particles back into the load-carrying skeleton, which is thought to enhance the stiffness of the soil skeleton. During shear, the unit normal vector of the large particle-to-large particle (L–L) contact has the strongest fabric anisotropy, and the S–S contact unit normal vector possesses the weakest anisotropy, suggesting that the large particles play a dominant role in carrying the shear load. It is also found that, during shear, fine particles are prone to rolling at contacts while the large particles are prone to sliding, mainly at the S–L and L–L contacts.

Introduction

Over the past several decades, many laboratory investigations have been carried out in terms of the shear behavior of clean sands, and the behavior has been successfully described in the framework of critical state soil mechanics (CSSM). However, observations from the failures of soil structures involving sands (Ishihara, 1993; Seed & Harder, 1990) indicate that most in situ sands generally comprise a certain quantity of fine particles <0.074 mm in diameter. These are referred to as silty sands in geotechnical engineering practice and the mechanical behavior of silty sands, because of the presence of the fine particles, is complex and not yet fully understood.

A review of published laboratory studies on silty sands (Chu & Leong, 2002; Georgiannou, Burland, & Hight, 1990; Kuerbis, Negussey, & Vaid, 1988; Murthy, Loukidis, Carraro, Prezzi, & Salgado, 2007; Ni, Tan, Dasari, & Hight, 2004; Pitman, Robertson, & Sego, 1994; Thevanayagam & Mohan, 2000; Yamamuro & Lade, 1997; Yang & Wei, 2012; Zlatović & Ishihara, 1997) indicates that the CSSM theory does not adequately describe the behavior of silty sands. For example, it was reported by Yamamuro and Lade (1997) that silty sand specimens with the same fines content, sheared at different consolidation pressures, tended to demonstrate a "reverse behavior" in that an increase in the consolidation pressure gave rise to an increase in dilation and enhanced the ability of the specimen to resist liquefaction. This is contrary to the normal behavior of clean sands predicted by the CSSM theory. The study of Thevanayagam and Mohan (2000) also showed that two silty sands, having the same initial global void ratio and fines content, behaved in a manner that could not be described in the framework of CSSM: the specimen at a higher confining pressure exhibited higher shear strength at a steady state.

The state parameter ψ, defined as the difference between the current global void ratio and the critical void ratio at the same mean effective stress (Been & Jefferies, 1985), is a useful parameter in describing sand behavior in the framework of CSSM (Li & Dafalias, 2000; Wood, Belkheir, & Liu, 1994; Yang & Li, 2004; Yang, 2002). The state parameter, however, does not work effectively for silty sand. As shown in Fig. 1(a), Foundry sand with a specific fines content of 12% shows a trend of decreasing contractiveness with increasing ψ (Thevanayagam & Mohan, 2000), a reverse trend compared with clean sand (Fig. 1(b)). In particular, many published studies have found that no unique critical state line can be determined in the e–log p' plane for silty sand (Been & Jefferies, 1985; Murthy et al., 2007).

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http://dx.doi.org/10.1016/j.partic.2014.08.010
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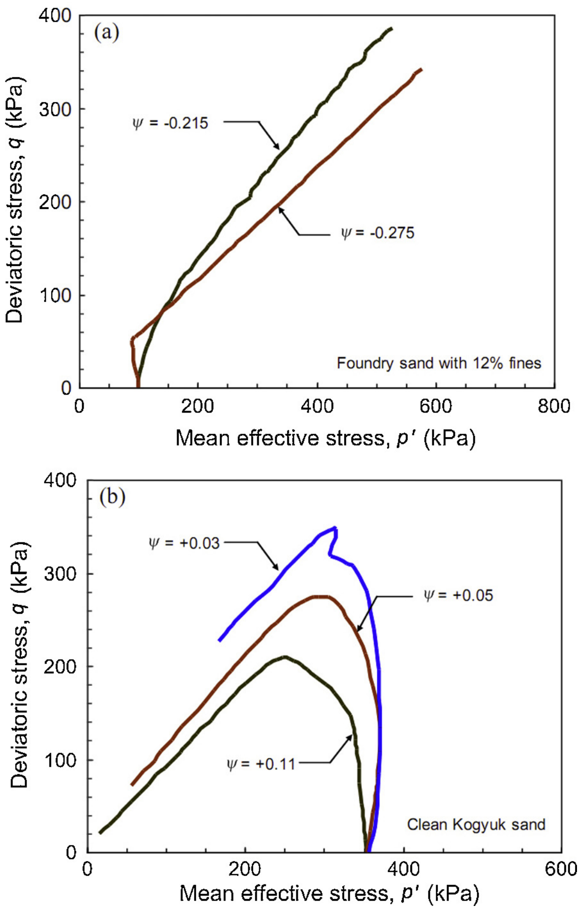

Fig. 1. Influence of state parameter on the shear behavior of granular soil: (a) foundry sand with fines (Thevanayagam & Mohan, 2000) and (b) clean Kogyuk sand (Been & Jefferies, 1985).

Some researchers have ascribed the incompatibility of the framework of CSSM with silty sand to the use of the global void ratio or ψ (Bobei, Lo, Wanatowski, Gnanendran, & Rahman, 2009; Georgiannou et al., 1990; Lade & Yamamuro, 1997; Mitchell, 1976; Ni et al., 2004; Rahman, Lo, & Gnanendran, 2008; Thevanayagam & Mohan, 2000). These authors considered that the fine particles were easily trapped in the voids formed between large particles and hence made little contribution to the force chains. In this respect, an alternative state variable, known as the skeleton void ratio, e_s, was proposed for silty sand by treating all of the fine particles as void spaces (e.g. Georgiannou et al., 1990; Mitchell, 1976). This index was then modified as an equivalent skeleton void ratio e_{se} by introducing a parameter, b, that considers partial participation of fine particles in the force chains (e.g. Ni, Tan, Dasari, & Hight, 2004; Thevanayagam, Shenthan, Mohan, & Liang, 2002):

$$e_{se} = \frac{e + (1-b)fc}{1-(1-b)fc}, \qquad (1)$$

where e is the global void ratio, fc is the fines content, and b denotes the portion of fine particles present in the force chains. Several issues were clarified by the use of the equivalent skeleton void ratio. First, a unique critical state line could be determined in the e_{se}–log p' plane by the best-fit approach using a back-calculated b value (Rahman et al., 2008; Thevanayagam, Shenthan, Mohan, & Liang, 2002; Yang, Sandven, & Grande, 2006). Notably, however, the factor b was treated in these studies as a constant throughout the loading process, which does not reflect its originally defined physical meaning (Dai, 2010).

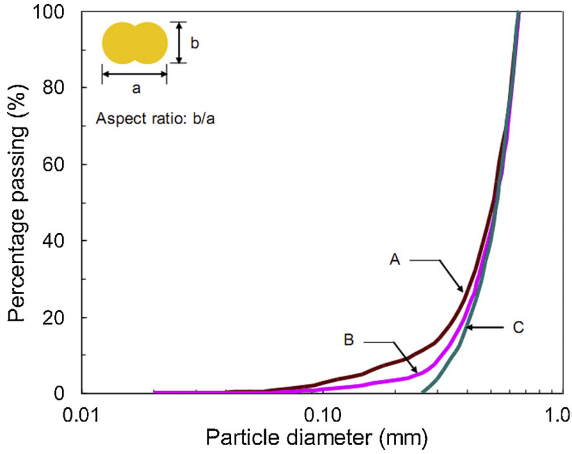

Fig. 2. Particle shape and size distributions considered in this study. Grading curve A has 10% particles <0.26 mm and $fc \sim 2\%$, grading curve B has 5% particles <0.26 mm and $fc \sim 1\%$, and grading curve C represents clean sand with grains in the 0.26–0.66 mm size range.

The complexity in the behavior of silty sand arises from its particulate nature, and particularly the presence of the fine particles. To develop a fundamental understanding of the shear properties of silty sand, it is necessary to examine the spatial arrangements of the fine particles in the soil skeleton and their interactions with coarse particles during the loading process. This is the motivation of this work and, by means of grain-scale modeling using the discrete element method (DEM) (Cundall, 1971), a series of numerical simulations have been performed and the results are presented and interpreted.

DEM model and data interpretation

Numerical model implementation

The program PFC2D (Itasca, 2005) was used to conduct biaxial test simulations in undrained conditions. Numerical specimens were composed of idealized particles, each of which had two circular constituent particles clumped together (Fig. 2) to take into account the non-circular shape of soil particles. Each clumped particle was assumed to behave as a rigid body with an aspect ratio of 0.6, and the two constituent particles were not allowed to break apart during loading. The size of a clumped particle was described by an equivalent particle diameter – the diameter of a circular particle with the same cross sectional area as the clumped particle. The linear elastic contact model was used to describe the contact behavior between particles, and the friction behavior at contacts was assumed to observe the Coulomb friction law. Both the normal and tangential stiffnesses of the contact were assumed to be 1.0×10^9 N/m, and a friction coefficient of 0.5 was adopted.

Three grading curves were considered in this study (Fig. 2). Grading curve C serves as the reference curve, representing clean sand with particles in the size range of 0.26–0.66 mm. To study the effect of fines, different amounts of finer particles were added to form two different materials, as represented in grading curves A and B. Grading curve A represents a silty sand with 10% particles <0.26 mm and $fc \sim 2\%$. Grading curve B represents a silty sand with 5% particles <0.26 mm and $fc \sim 1\%$.

All numerical specimens were prepared using the gravitational deposition method. As illustrated in Fig. 3(a), particles with random orientations were initially generated in a designated domain, and the gravity field was then introduced with the gravitational forces applied to all particles in a vertical direction. In doing so,