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A micromechanical analysis of the effect of fabric on low-strain stiffness of granular soils

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ABSTRACT

The effect of fabric on low-strain shear stiffness properties of granular soils was assessed using Discrete Element simulations. These soils were idealized as a collection of non-spherical particles that interact according to Hertz's contact law. Different fabrics of the same soil were obtained by extracting particles from the weak or strong interparticle force networks. The associated stiffness properties were evaluated for various levels of isotropic triaxial confining stress conditions. The conducted analyses showed that a soil with a given void ratio and level of confining stress may have various fabrics associated with noticeably different low-strain shear moduli. The mechanical coordination number and particle shape were found to be the main factors that dictate the low-strain stiffness properties of a certain granular soil (with a specific contact law). For a defined level of confining stress, the shear stiffness of a particular soil is shown to be linked to the mechanical coordination number by a unique relation.

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1. Introduction

Granular soils consist basically of an assemblage of discrete mineral particles of various sizes and shapes. The geometrical and mechanical characteristics of the particles as well as their arrangement have a significant influence on the soil macroscale mechanical properties and response [e.g., 1–3]. From an engineering perspective, the macro-scale stiffness parameters at very low-strain are among the most essential characteristics needed to conduct an analysis of static or dynamic response of these soils. A significant body of experimental research has been devoted to these parameters over the last five decades. In the 1960s, Hardin and Richart [4] showed that the low-strain shear modulus of granular soils is strongly dependent on mean effective stress and void ratio. Hardin [5] also found that the loading history (e.g., overconsolidation) has only a minor effect. Numerous other studies were conducted over the years [e.g., 3,6,7]. Some of these studies explored the effects of factors such as grain size distribution, particle shape, and anisotropy on the shear modulus. For instance, Cho et al. [2] assessed the influence of particle shape on the low-strain stiffness properties of sands. Some authors [3] and [8] showed that elastic properties of granular soils are also a function of particle size distribution.

Natural and engineered granular soil deposits are formed in a number of different ways, including dry and hydraulic depositions. The deposition method has a significant effect on soil fabric. The term fabric is used in the literature (and herein) to refer to the packing or spatial arrangement of discrete particles and associated voids [9,10]. In turn, the variations in fabric affect the soil mechanical properties [11,12]. Laboratory tests were conducted by a number of researchers to investigate the effect of fabric on the elastic properties of granular soils. For example, Kasantikul [13] used both dry pluviation and wet deposition to demonstrate that the low strain stiffness properties of granular soils are affected by differences in sample preparation. Dobry and Abdoun [14] clearly documented in a laboratory setting the effect of deposition method. The normalized shear wave velocity of two Ottawa sand deposits having the same void ratio and created by hydraulic fill and dry pluviation were found to be 113 m/s and 174 m/s, respectively. Also some authors [15] and [16] showed that pre-straining of granular soils affects their structure and leads to an increase in shear modulus. On the other hand, Kokusho [7] suggested that the shear modulus of sands is rather insensitive to the method of sample preparation.

Micromechanical analyses have been also conducted to evaluate the low-strain properties of granular soils. These analyses enable an effective assessment of the significance of factors that are not readily accessible through experimentation, such as coordination number (i.e., average number of contacts per particle) and spatial distribution and orientation of contacts [e.g., 17–19]. Chang and co-workers [20,

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21,22, 23] employed homogenization along with kinematic and static hypotheses to obtain expressions for the shear modulus of a random packing of particles as a function of void ratio, coordination number and confining stress. Emeriault and Cambou [24] derived a similar expression as a function of the number of interparticle contacts per unit of volume and confining stress. Agnolin and Roux [25] showed that the elastic moduli of an assemblage of mono-size spherical particles are "chiefly sensitive to the coordination number."

In this study, the Discrete element method (DEM) is used to model granular soils as a collection of non-spherical particles. The employed model is used along with numerical simulations to evaluate the effect of fabric on the low-strain shear stiffness properties of granular media and assess the link between micro-scale characteristics and macro-scale stiffness attributes.

2. Modeling of granular soils

A complete modeling of a granular soil using a discrete approach requires specification of the geometrical and mechanical characteristic of the individual particles, and description of the arrangement of the associated (particle) assemblage. The mechanical characteristics are provided by the interparticle contact laws. The packing is often dictated by the method used to generate the assemblage and generally described by a fabric tensor. The equilibrium conditions of the assemblage are achieved by ensuring the balance of momentum of each of the individual particles.

2.1. Geometrical particle characteristics

Granular soils are composed of discrete particles that have experienced different types and levels of weathering, and consequently have various shapes, as illustrated for instance in Fig. 1 by few Ottawa sand grains. In this study, these soils are modeled as a collection of idealized non-spherical DEM particles. These particles were obtained by clumping and enslaving multiple spheres. The enslaved spheres behave mechanically as single entities that interact solely at the points of contact with neighboring clumps [26]. Such particles simulate soil grains in a more realistic fashion than simple spheres and allow the possibility of studying the influence of particle shape. This paper focuses on assessing the effect of soil fabric on low strain stiffness for the same assemblage of particles that have specific (non-spherical) shapes.

The conducted DEM simulations employed a basic assemblage of particle, labeled herein as *synthetic soil*. This soil consisted of two-, three- and four-sphere clumps (with various levels of sphere overlap) as particles (Fig. 1). Globally, these particles classify as rounded (with smoothly curved sides and no edges), as shown in Table 1 by the average values of sphericity and roundness [27]. The particle-size distribution of the *synthetic soil* corresponds to a uniform coarse sand, with equivalent diameters ranging from 0.6 mm to 2.0 mm and a coefficient of uniformity equals to 1.5, as shown in Fig. 2. Such a distribution was employed to ensure a manageable number of particles and time step of the explicit DEM calculations (which is inversely proportional to the size of the smallest particles [26]). In addition to the synthetic soil, some simulations were also conducted using an assemblage constituted solely of *spherical particles* having the same size distribution.

2.2. Particle equations of motion

In the DEM method, each particle is treated individually [28]. The particles are subjected to external field forces, such as gravity,

Table 1
Particle shape characteristics of analyzed synthetic soil and two soils commonly used in experiments.

Particle type	Sphericity (*S*)	Roundness (*R*)
Synthetic soil	79	93
Spheres	100	100
Ottawa sand [55]	78	65
Nevada sand [2]	85	60

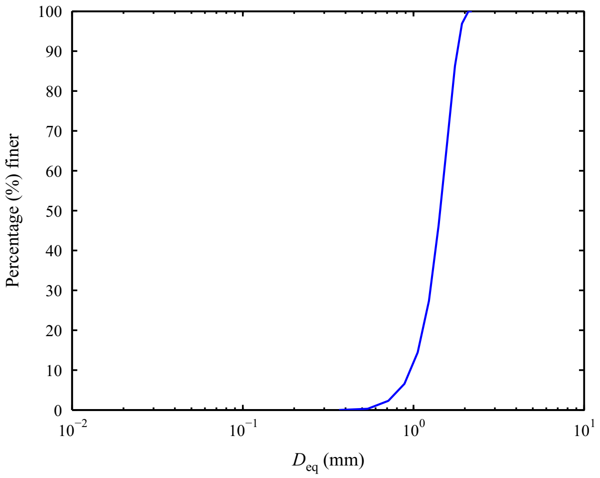

Fig. 2. Grain size distribution of the analyzed synthetic soil (D_{eq} is the diameter of an equivalent sphere having same volume as a corresponding non-spherical particle).

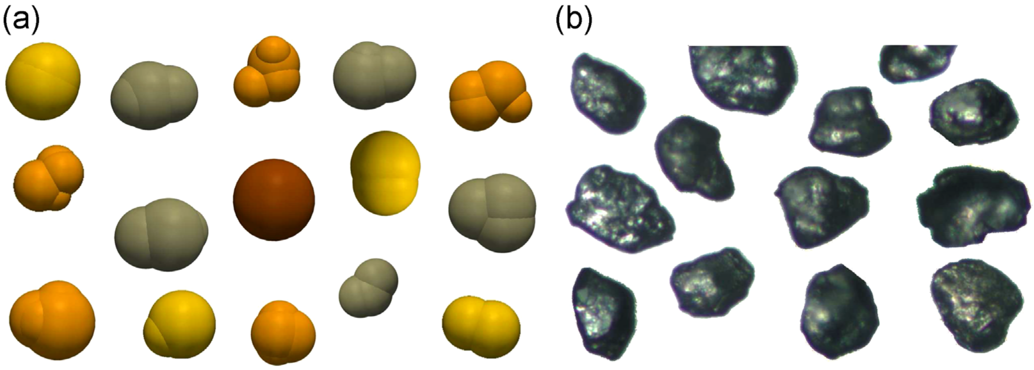

Fig. 1. Particle shapes. (a) Sample of particles used in the conducted simulations. (b) Selection of Ottawa sand particles.

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