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Image-based investigation into the primary fabric of stress-transmitting particles in sand

J. Fonseca[a,*], S. Nadimi[a], C.C. Reyes-Aldasoro[a], C. O'Sullivan[b], M.R. Coop[c]

[a]City University London, UK
[b]Imperial College London, UK
[c]University College London, UK (formerly City University of Hong Kong, H-K)

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Abstract

This paper uses three-dimensional images of a natural silica sand to analyse the mechanisms of stress transmission under triaxial compression. As discussed in Fonseca, J., O'Sullivan, C., Coop, M., Lee, P.D., (2012), the irregular morphology and locked fabric that can be found in natural sands lead to the formation of contacts with extended surface areas. However, most of our current understanding of stress-transmission phenomena comes from DEM simulations and photo-elastic experiments using idealised grain shapes and contact topologies. The direct measurement of stress transmission in assemblies of real soil grains is a challenging task. The present study postulates that important insight can be obtained by following the evolution of intergranular contacts as the grains rearrange and by considering how these rearrangements enhance the stability of the material. The methodology consists of measuring the geometrical data of the individual grains and their associated contacts obtained at successive load stages in the post-peak regime (after shear band formation). A statistical analysis of the vectors normal to the contacts reveals a realignment of these vectors in the direction of the major principal stress; this is a clear indication of the formation of force chains. A subsequent analysis shows that these columnar structures of stress-transmitting grains are associated with larger contact surfaces and have distinct patterns in the regions affected by the formation of a shear band. An algorithm based on stability and load-transmission criteria is developed to contribute new insight into the characterisation of load-bearing sand particles.

Keywords: Fabric/structure of soils; 3D microscopy; Shearing; Locked sand; Stress-transmission

IGS: D01; D03; D06

1. Introduction

Inter-particle stress transmission is a key factor that determines the mechanical behaviour of granular materials, including soil. Recent decades have witnessed significant advances in our understanding of the physical principles that underpin stress-transmission phenomena. Photo-elastic experiments and discrete element method simulations have provided evidence that stress transmission in granular materials takes place through well-defined paths termed force chains (Ostojic et al., 2006; Silbert et al., 2002; Tordesillas et al., 2010; Zuriguel et al., 2007; Radjai et al. 1998). Force chains are columnar-like structures formed by the particles that carry the majority of the load in the system (Majmudar and Behringer, 2005; Lin and Tordesillas, 2014). This subset of particles, often defined as those carrying above average contact forces, is referred to as the strong network. Surrounding the force chains

*Corresponding author.
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are the particles in the complementary weak network, the subset of contacts not in the strong network, which serve to provide the necessary support to the chains (Tordesillas and Muthuswamy, 2009; Barreto and O'Sullivan, 2012). Under continued loading and the loss of lateral support due to dilatation, these axially compressed particle columns that are the strong network become unstable and prone to buckling; this has been related to the formation of shear bands (Oda and Kazama, 1998; Rechenmacher et al., 2010; Tordesillas et al., 2012). Clear experimental evidence of the formation of force chains in sandstone has been provided by Fonseca et al. (2013a); the rupture of the cement between grains during triaxial compression leads to the formation of vertical columns of horizontally unbonded grains, which tend to collapse in localised regions during the shearing process.

Forces are transmitted only through the interparticle contacts; the non-uniformity of the size and the orientation of these contacts, as well as the variation in the properties of the particles forming the contacts, lead to strong inhomogeneities in the force chains (Radjai et al., 1998). Under shear, an anisotropic contact network develops because some new contacts are formed along the major principal stress, while others are lost perpendicular to it. This was observed in experiments with sands (Oda, 1972; Fonseca et al., 2013b) and DEM simulations (Rothenburg and Bathurst 1989; Thornton, 2000). Radjai et al. (1998) showed that since the strong network continually aligns in the direction of the most compressive principal stress, it is more anisotropic than the weak network.

Tordesillas et al. (2010) introduced the concept of force cycles to characterise the mutually supportive structures, analogous to structural trusses, that emerge during granular material deformation and which prevent failure. Tordesillas et al. observed that force chains tend to stabilise under 3-cycle contact triangle topologies (triangular trusses) with neighbouring grains. These 3-cycle contacts are more effective than other contact topologies in providing resistance to loading by inhibiting relative particle rotations and providing strong lateral support to force chains (e.g., Tordesillas et al., 2011). The three-force cycles act to support the load and secure the stability of the force chain columns. Loss of contacts and the rupture of 3-force cycles leads to force chain failure due to buckling.

The characterisation of force chains is commonly achieved by discriminating between forces of different magnitudes (Ostojic et al., 2006). Force chains can be visually identified by representing the contact forces as lines whose thickness and/or colour indicates magnitude (Voivret et al., 2009; Radjai et al., 1998). The complexity and non-linearity of the force chains in 3D have been shown by identifying the paths of maximum contact force (Makse and Johnson, 2000). Peters et al. (2005) characterised force chains in an assembly of disks based on the principles of quasi-linearity and stress concentration. Zuriguel et al. (2007) used a least squares estimation to fit straight lines to chains identified in photo-elastic experiments; they observed a well-defined correlation between the orientation of the chains and the angular distribution of the contacts. Zuriguel et al. also reported on different modes of stress transmission for the case of disks when compared with the sample of elliptic cylinders. The splitting and merging of the force chain paths through granular media were investigated by Bouchaud et al. (2001). Hanley et al. (2015) used a simple link-node model to show that the peak major principle stress these force chains can resist is directly proportional to the confining stress, in line with Mohr-Coulomb's failure criterion.

The current study makes use of x-ray micro-computed tomography (micro-CT) coupled with three-dimensional (3D) image analysis tools to investigate the network of stress transmission in specimens of real sand. This comprehensive study follows the preliminary work presented in Fonseca et al. (2014). Following the description of the material and the experimental methods, a statistical analysis of the orientation of the contact vectors, comprising both the contact normal vectors and branch vectors, is presented. Then, the spatial distribution of these vectors is investigated to provide insight into the networks of stress-transmitting particles.

2. Material and methods

This section describes the sand used in the experiments as well as the sampling technique applied to obtain the intact specimens and the sample preparation technique of the reconstituted samples. The methodology employed here consists of carrying out triaxial tests, impregnating the samples with resin to preserve the fabric at various stages of deformation, extracting small cores for imaging at different locations and finally analysing the 3D images in order to obtain the required information in terms of grain rearrangements and contact evolution under loading. Only the key aspects are described here; further details on the material and the experimental procedures can be found in Fonseca (2011).

2.1. Reigate sand

Reigate sand, the material used here, comes from a formation that is part of the Folkestone Beds (Lower Greensand) from Southeast England in the UK. In its intact state, Reigate sand is characterised by very high densities and a locked fabric; it meets the “locked sand” criteria proposed by Dusseault and Morgensten (1979). This locked fabric enabled the use of block sampling; and thus, effectively undisturbed samples were considered in this experimental study, as discussed in more detail in Fonseca (2011). In its intact state, Reigate sand is a quartz-rich sand with a median grain diameter of approximately 300 μm (this value decreases for samples prepared in a laboratory, as discussed in Fonseca et al., 2012). The particle morphology varies from near-spherical grains to highly non-spherical grains with embayments. The microstructural characteristics to note include the abundance of large flat and concavo–convex contacts, in most cases forming multiple contact regions. These features are evident in the optical microscope image of the intact sand presented in Fig. 1. In addition, fissures within the solid grains are also commonly found in this geologically old, once deeply