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A characterization of the coupled evolution of grain fabric and pore space using complex networks: Pore connectivity and optimized flows in the presence of shear bands

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ABSTRACT

A framework for the multiscale characterization of the coupled evolution of the solid grain fabric and its associated pore space in dense granular media is developed. In this framework, a pseudo-dual graph transformation of the grain contact network produces a graph of pores which can be readily interpreted as a pore space network. Survivability, a new metric succinctly summarizing the connectivity of the solid grain and pore space networks, measures material robustness. The size distribution and the connectivity of pores can be characterized quantitatively through various network properties. Assortativity characterizes the pore space with respect to the parity of the number of particles enclosing the pore. Multiscale clusters of odd parity versus even parity contact cycles alternate spatially along the shear band: these represent, respectively, local jamming and unjamming regions that continually switch positions in time throughout the failure regime. Optimal paths, established using network shortest paths in favor of large pores, provide clues on preferential paths for interstitial matter transport. In systems with higher rolling resistance at contacts, less tortuous shortest paths thread through larger pores in shear bands. Notably the structural patterns uncovered in the pore space suggest that more robust models of interstitial pore flow through deforming granular systems require a proper consideration of the evolution of *in situ* shear band and fracture patterns – not just globally, but also *inside* these localized failure zones.

1. Introduction

The behavior of granular materials under load bears a tremendous influence on everyday life. This ranges from support to buildings (Yun et al., 2013; Zhang et al., 2014), geological hazards like landslides and earthquakes (Aharonov et al., 2013), production and storage of oil and gas (Jang et al., 2011; Kress et al., 2012; Yun et al., 2014), to the processing and transport of agricultural grains, pharmaceutical pills and chemical powders (Duran, 1997). Despite the long-standing research interest into granular media behavior (Duran, 1997; Carman, 1937; Lenoe, 1966), the coupled mechanics of deformation and interstitial matter flow in granular systems remains poorly understood (Sun et al., 2013; Tordesillas et al., 2013). Conventional approaches are limited since these generally treat the solid grain fabric and the interstitial pore space independently of each

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other, effectively ignoring the strong interdependencies between these two phases.

Studies of the solid grain fabric, combining knowledge and tools from structural and soil mechanics (Oda and Iwashita, 1999; Tordesillas and Muthuswamy, 2009; Rechenmacher, 2006; Rechenmacher et al., 2010) and complex networks (Smart and Ottino, 2008; Arévalo et al., 2010; Rivier and Fortin, 2013), have shed light on the physical mechanisms underlying strength and failure of granular materials (Bagi, 2007; Kuhn and Chang, 2006; Muthuswamy and Tordesillas, 2006; Tordesillas and Muthuswamy, 2009; Tordesillas et al., 2011, 2014, 2015). Similarly, important insights into the transport of gas

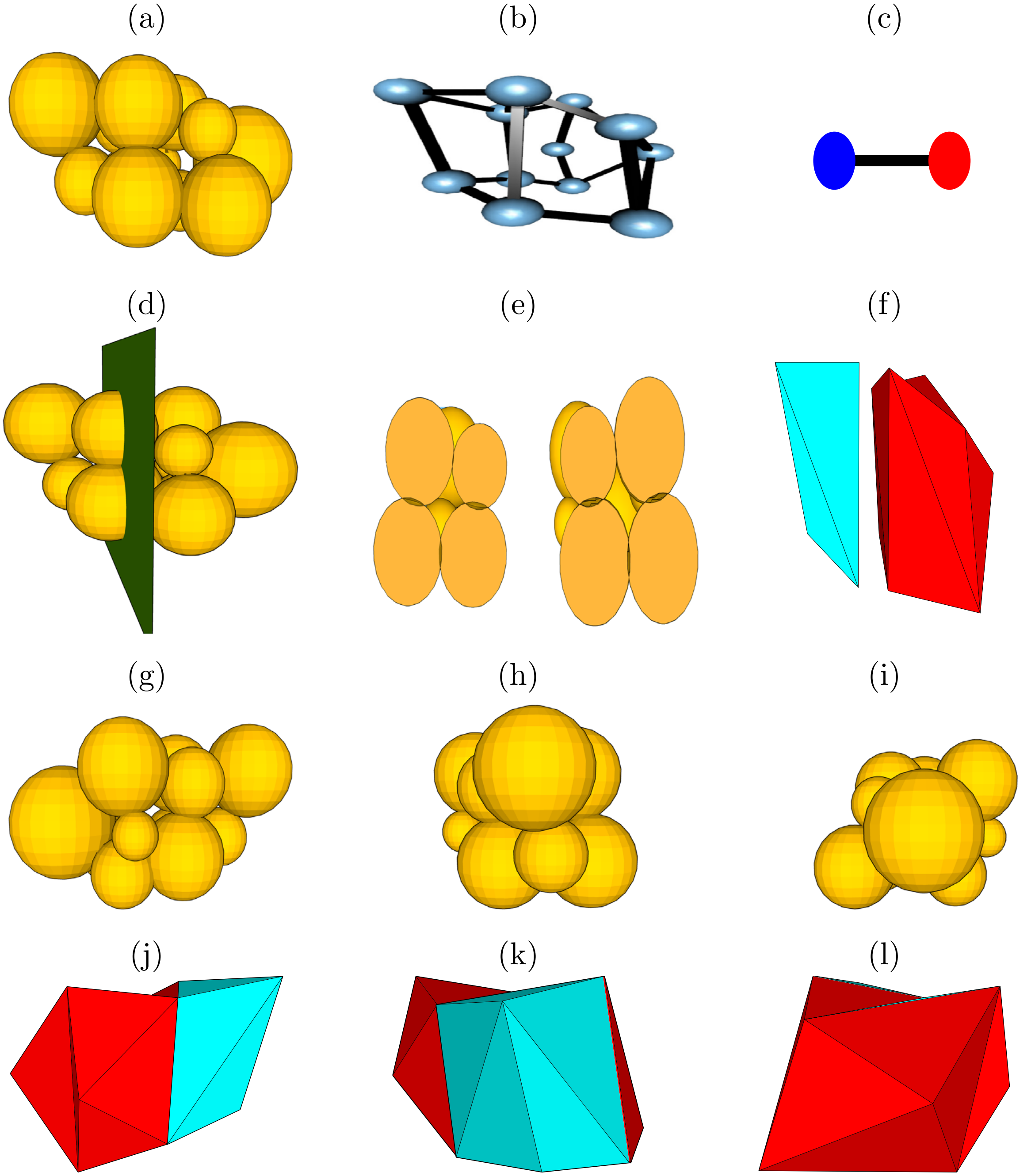

Fig. 1. Constituent polyhedral elements representing the internal pore phase of a granular assembly. (a) A small assembly of grains; (b) its contact network, where each node (edge) represents a grain (contact), capturing the connectivity of the solid grains and local pore space geometry; and (c) the pore space network representing the connectivity of the pores. (d) Cross-sectional cut along the common face of the polyhedra: (e) views into the left and right pore spaces, (f) blue (light) tetrahedron representing the left pore space and red (dark) polyhedron representing the right pore space, separated to show the shared face. Other views of the granular assembly and associated polyhedra: (g and j) from the back, (h and k) from the left and (i and l) from the right. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

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