In-situ X-ray Tomography and Diffraction: Probing Granular Micromechanics and Energy Dissipation During Compaction

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Summary: We combine *in-situ* X-ray computed tomography (XRCT) with 3D X-ray diffraction (3DXRD) to measure both particle kinematics and particle stresses during deformation of granular samples. Using this approach, we can calculate inter-particle forces, contact kinematics, and energy dissipation throughout the deformation process, providing new insight into the statistics and spatial heterogeneity of these processes.

1. INTRODUCTION

Our past work has demonstrated that a combination of *in-situ* 3D X-ray diffraction (3DXRD) [1] and X-ray computed tomography (XRCT) measurements, obtained during the deformation of granular materials, can be used to quantify inter-particle force vectors, stress and strain fields and their relationship to microstructure, and intra- and inter-particle stress states preceding and following particle fractures [2, 3]. Here, we will present a novel use of *in-situ* 3DXRD and XRCT measurements for quantifying contact mechanics and energy dissipation during uniaxial compression of two samples of granular materials with varying degrees of lateral confinement. We will show that inter-particle forces evolve distinctly in the two samples, and will highlight the observation that many quantities, including inter-particle forces, energy dissipation, twisting angles, and slip distances, all obey similar statistical distribution functions, but with different parameters. We will discuss the implications of these findings for understanding the mechanics of granular materials across length scales.

2. EXPERIMENTAL METHOD

Experiments were performed at beamline ID11 of the European Synchrotron Radiation Facility (ESRF). Two samples of approximately 900 near-spherical ruby particles, with diameters of 140 μm - 150 μm, and surface roughness of 0.008 μm, were subjected to uniaxial compression in custom-built load frames that provided varying degrees of lateral confinement. The load frames are described in detail elsewhere [4]. The first experiment, T1, involved compressing the ruby particles within an aluminum sleeve by imposing small increments of vertical sample strain. The second experiment, T2, involved initially compressing the sample isotropically within a membrane submerged in a pressurized fluid cell in 1 MPa pressure increments (to 3 MPa isotropic pressure) before imposing small increments of vertical sample strain. After each pressure and strain increment in both experiments, XRCT and 3DXRD measurements were made by rotating the sample 360° and 180°, respectively, while it was illuminated by a 55 keV monochromatic X-ray box beam larger than the sample. Using the 3DXRD and XRCT data, we segmented particles and tracked their locations, orientations, and individual strain tensors across load steps [2, 3]. Inter-particle force vectors were inferred at each inter-particle contact, and slip distances, rolling distances, twisting angles, and energy dissipation were then quantified at each contact [4].

3. RESULTS

Figures 1(a) and 1(b) show XRCT images of samples at the end of experiments T1 and T2, respectively. Figures 1(c) shows the trajectories of particle centroids across all load steps in experiment T2, highlighting the significant

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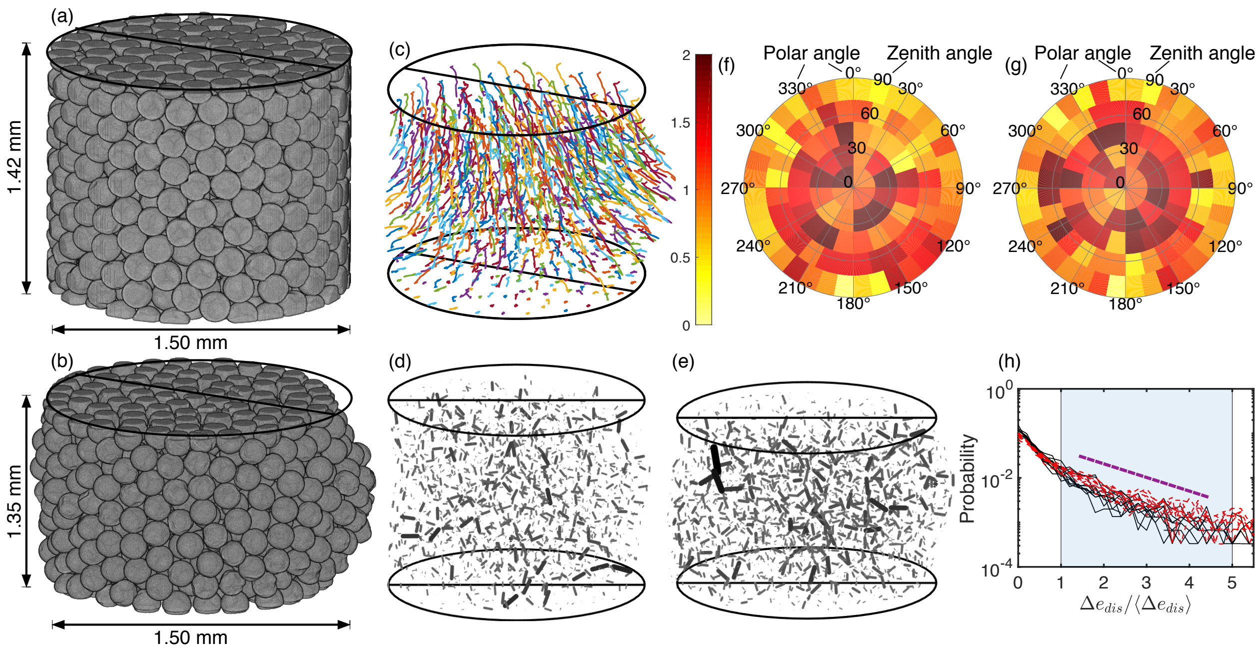

Figure 1: (a), (b): XRCT images of the two samples at the end of the experiments (labeled height is initial). (c): particles' trajectories across all load steps in experiment T2. (d), (e): inferred inter-particle forces at two load steps in experiment T2. Force vectors are scaled linearly in width and length by force magnitude. (f), (g): Lambert azimuthal equal-area projections of orientations of strong forces corresponding to (d) and (e), respectively. Colors represent the ratio of force vectors per bin divided by median number of force vectors across all bins. Angles around the projection perimeter correspond to the polar angle of force vectors. The other angles corresponds to the zenith angle of force vectors. (h): probability distributions of energy dissipated at all inter-particle contacts. Different curves correspond to different load steps of experiment T1 (black solid lines) and T2 (red dashed lines).

particle motion in this experiment, distinct from particle motion observed in experiment T1 (not shown). Figures 1(d) and 1(e) show inferred inter-particle forces at two load steps in experiment T2. A significant change in the magnitude and orientation of large forces can be observed between the two load steps. Figures 1(f) and 1(g) show Lambert azimuthal equal-area projections of strong force orientations (those with magitudes greater than the mean force) [5] for the same load steps captured in Figs. 1(d) and 1(e). A close observation reveals that strong forces become more horizontally aligned in Fig. 1(g), with higher probability density toward the perimeter of the projection (corresponding to horizontal force alignment) than the center of the projection (corresponding to vertical force alignment). Figure 1(h) illustrates that the probability distribution of inter-particle energy dissipation, Δe_{dis}, follows an exponential distribution for both experiments at each load step (black lines are T1, red lines are T2), but with different slopes that depend on the macroscopic load level.

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