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Challenges and opportunities in measuring time-resolved force chain evolution in 3D granular materials

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Granular materials are found throughout nature and industry: in landslides, avalanches, and river beds, and also in pharmaceutics, food, and mineral processing. Many behaviors of these materials, including the ways in which they pack, deform, flow, and transmit energy, can be fully understood only in the context of inter-particle forces. However, we lack techniques for measuring 3D inter-particle force evolution at subsecond timescales due to technological limitations. Measurements of 3D force chain evolution at subsecond timescales would help validate and extend theories and models that explicitly or implicitly consider force chain dynamics in their predictions. Here, we discuss open challenges associated with force chain evolution on these timescales, challenges limiting such measurements, and possible routes for overcoming these challenges in the coming decade.

I Introduction

Granular materials play prominent roles in landslides, avalanches, earthquakes, and river-bed mass transport, as well as in the pharmaceutical, food, and mineral processing industries [1–3]. The statistics, fluctuations, and organization of force chains – inter-particle forces with magnitudes greater than the average in a cohesion-less material – have been linked to: material stresses [4]; electrical and mechanical energy transport [5–8]; mechanical failure via particle fracture and inter-particle slip [9, 10]; mechanical failure of confining vessels due to stress concentrations [11]; stick-slip on granular fault gouge [12]; hot spot formation during compaction of energetic powders [13]; the dynamics of intruders penetrating granular beds [14]. However, measuring time-resolved 3D force chain evolution at timescales relevant to these and other applications remains a challenge due to technological limitations and the difficulty of such experiments. Here, we therefore summarize several open challenges related to dynamic force chain evolution at subsecond timescales, describe the challenges associated with such measurements, and propose possible routes for overcoming these challenges in the coming decade.

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i A brief history of force measurements

Researchers have pursued techniques to measure inter-particle forces in granular media since at least the 1970s [19]. Both 2D and 3D methods have been developed. 2D methods using photoelastic and rubber discs have been most commonly used [20, 21], as described in depth in several recent review articles [22, 23]. Such methods must employ 2D grains that are more compliant and possess slower wave speeds than grains in many natural and industrial applications of granular materials. While the compliant nature of photoelastic grains may alter the interactions of grains relative to their natural counterparts, the slower wave speeds have a benefit: the ratio of compaction wave speed to loading velocity in photoelastic granular matter may be similar to that in dynamically-loaded natural sands even when the loading velocity in the photoelastic case is significantly slower. This change in the timescales of information flow allows comparable dynamic processes, such as penetration, to be imaged at significantly reduced frame rates in 2D photoelastic granular matter as compared to 3D natural granular matter [14].

Despite the differences in compliance, wave speeds, and dimensionality, 2D photoelasticity studies have revealed the role of force chain statistics and fluctuations on mechanical properties [20], stick-slip [24], dynamic penetration and compaction [13, 14, 25], and electrical and mechanical wave transmission [6, 8]. A benefit of studies employing 2D photoelastic and rubber discs is that measurements can be made over very short timescales using high-speed imaging. This has enabled studies of force chain dynamics at subsecond (down to millisecond) timescales relevant to processes such as stick-slip, dynamic compaction, and wave transmission [7,18,24–26]. Unfortunately, many dynamic processes in granular materials occur in 3D rather than 2D, motivating the need for quantifying dynamically-evolving forces in 3D.

Advances in 3D full-field imaging, including in confocal microscopy, refractive index-matched scanning (RIMS), and X-ray computed tomography and diffraction, have enabled the first force measurements in 3D over the past two decades [27–30]. These advances have recently enabled relating force chain evolution to quasi-static granular deformation, failure, and wave transmission [8, 9, 29]. A prevailing challenge impeding 3D measurements of dynamic force chain evolution is the limited timescales accessible by full-field imaging techniques. For example, in 2012, RIMS was possible with 10 ms exposure time per image, enabling full-field imaging of a 3D granular medium in about one second [27]. However, data transfer rates and maximum write speeds of hard drives were the limiting factors hindering faster RIMS measurements. Even having overcome such technological limitations, it may be impossible to design a RIMS experiment to quantify subsecond force chain evolution in many cases of interest due to the interaction of index-matched fluids with granular dynamics on such timescales. As another example, 3D X-ray tomography measurements have been made in 20 seconds for glass beads and in less than one second for other materials such as batteries [31, 32]. Although tomographic imaging rates are expected to improve with new laboratory [33] and synchrotron [34] capabilities, most tomographic imaging requires sample rotation, which induces centrifugal forces. Such centrifugal forces are not present in many applications of interest for 3D granular materials and therefore limit the extent to which 3D force chain dynamics can be meaningfully studied using X-ray tomography.

These challenges associated with 3D measurement techniques have limited the experimental study of dynamic force chain evolution in a variety of applications in which they are thought to be important. In the next section, we describe several such applications that would benefit from time-resolved force chain measurements in 3D. We then describe key developments that may provide opportunities for overcoming the current timescale limitations of 3D inter-particle force measurements in the coming years.

II Open challenges related to force chain evolution

The following list summarizes open challenges related to time-resolved 3D force chain evolution in granular materials, and how measurements of such evolution would benefit our understanding and predictive capacity. Such measurements have not yet been made primarily because of the technological limitations and the difficulty of the associated experiments, as described in the prior section. Possible routes to overcoming these limitations and difficulties are described in Sec. III. The list of open challenges is partially summarized in Fig. 1.

1. *Stick-slip and intermittent flow (Fig.1(a))* – Force chain buckling has been considered a possible mechanism of stick-slip and acoustic emissions in sheared granular fault gouge for decades [12, 35–38]. Stress-drop events associated with stick-slip and force chain buck-

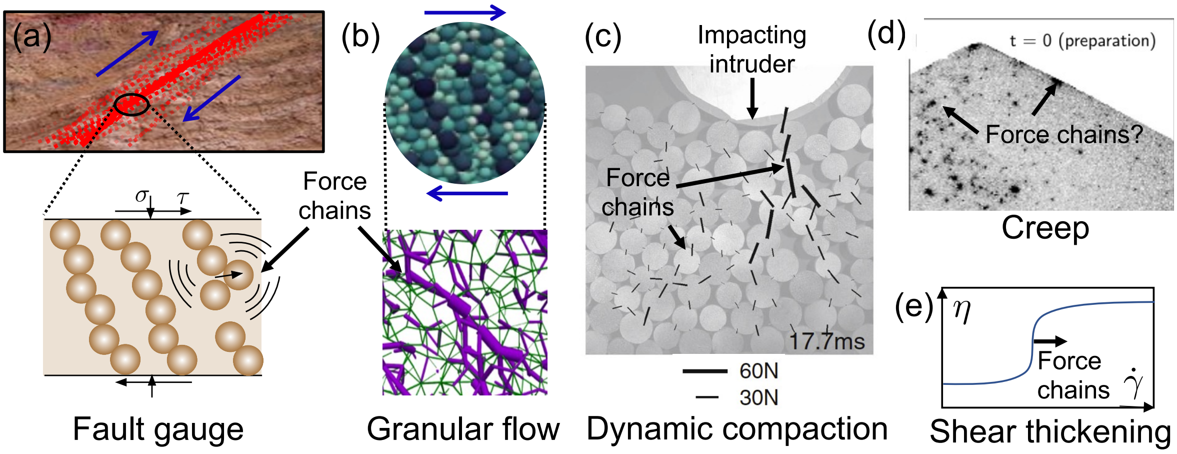

Figure 1: Open challenges in granular mechanics involving force chain dynamics include (a) chain buckling in fault gouge, (b) chain dynamics in granular flows, (c) stress concentrations during dynamic compaction, (d) force chain evolution during creep at the onset of catastrophic flow visualized through diffusing wave spectroscopy (DWS), and (e) force chain formation in discontinuous shear thickening. Images adapted from [15–17] (Open Access) and [18] with permission.

ling likely occur over millisecond timescales [39]. Experimental measurements of force chain buckling in granular fault gouge have been made only in model 2D photoelastic systems [24] and only with coarser time resolution (order of seconds) before and after stress drop events. Experiments employing 3D force chain measurements at short timescales, ideally with subsecond and approaching millisecond resolution, would support the notion that force chain buckling is responsible for stress drops and acoustic emissions in granular fault gouge. These measurements could be used to validate and extend models of fault gouge mechanics relevant to short timescales.

2. *Hypotheses underlying models of granular flow (Fig.1(b))* – Mathematical models of granular flow, such as non-local fluidity and shear transformation zone theories, feature non-local Laplacian terms and other quantities that capture the role of force fluctuations around the core of a rearrangement event [40–42]. Such force fluctuations likely occur over the millisecond timescales associated with stress drops [43]. Although the kinematics associated with such fluctuations have been made over longer timescales in 2D [44], they have not been made in 3D. Experiments quantifying 3D force fluctuations around rearrangement events at millisecond to second timescales would provide some of the first *in-situ* data with which to calibrate, validate, and extend models that explicitly or implicitly incorporate such fluctuations (e.g., [45, 46]).

3. *Stress concentrations and hot spots during dynamic compaction (Fig.1(c))* – Rapid compaction of granular media plays an important role in manufacturing, defense, planetary science, and manufacturing processes [47]. In energetic materials, force chains that develop during rapid compaction are also thought to nucleate hot-spots that eventually lead to material ignition [48]. Many compaction and ignition events of scientific and technological importance take place over millisecond or shorter timescales. Prior rapid-compaction and impact studies investigating force chains have primarily employed 2D photoelastic and polymer discs [13, 25, 49], or numerical simulations. Experiments quantifying force chain evolution during 3D granular compaction events would provide new insight into the joint evolution of porosity, stresses, and forces experienced by these materials, quantities currently available only through numerical modeling despite their critical importance for predicting the outcome

of impact and material processing events.

4. *Creep and the onset of catastrophic flow (Fig.1(d))* – Creep leading to catastrophic flow occurs in nature in a variety of granular media, including ice and snow prior to avalanches, soils prior to landslides, and river beds prior to submarine landslides [50]. Glassy dynamics and force chain fluctuations have been implicated in the progression of creep leading to the onset of flow [50, 51]; however, direct measurement of force chain evolution throughout the creep process has not been made in 3D. Two-dimensional measurements of creep have been made across a broad range of timescales and length scales using diffusing wave spectroscopy (DWS) (pioneered for granular matter by Crassous and colleagues [44, 52, 53]), but force measurements during the creep process have been made neither in 2D nor 3D. Depending on the the geometry and stresses imposed on a granular material, creep may occur over a range of timescales, from hours to seconds. Experimental measurements of 3D force chain evolution across this range of timescales would validate conceptual models of creep and provide valuable data supporting mechanistic model development.

5. *Force chain formation in discontinuous shear thickening (Fig.1(e))* – Discontinuous shear thickening (DST), the ubiquitous increase in viscosity with shear of flowing dense suspensions, is thought to be related to force chain development on millisecond timescales [54, 55]. Discontinuous shear thickening has been studied both experimentally and computationally, but no *in-situ* measurements of force chain development have been made in either 2D or 3D in such studies. Such direct measurements would provide vital information needed to calibrate and validate models of DST and related jamming phenomena in suspensions.

III Future opportunities for time-resolved force chain measurement

The following list summarizes key advances that may enable measuring time-resolved force chain evolution in 3D. It is not meant to be exhaustive but rather to reflect the current perspective of the authors. The list primarily contains technological developments that may enable full-field measurements on millisecond to second timescales. This list is also summarized in Fig. 2.

1. *High-speed RIMS with image-based force inference (Fig.2(a) and (d))* – RIMS allows full-field imaging of granular materials submerged in index-matched fluids and, as described in Sec. I, permits imaging rates around 1 Hz [27]. By combining RIMS with quantitative analysis of particle deformation (e.g., in hydrogels [56]), inter-particle forces can be inferred in 3D. Further advances in camera hardware and data storage capabilities may enable subsecond full-field imaging with RIMS. Imaging rates currently accessible by RIMS make it amenable to studies of stick-slip, non-local constitutive laws used to predict slow granular flows, and creep. Future subsecond imaging rates will improve resolution of individual force chain buckling events during such phenomena. Reducing full-field RIMS imaging rates far below subsecond resolution is unrealistic due to the interaction of the index-matched fluid dynamics with the "true" dynamics of a granular material. Nevertheless, we envision that carefully designed experiments employing RIMS may provide new and important insight into force chain fluctuations on second timescales in compliant materials like hydrogels.

2. *Time-resolved 3D X-ray imaging for compliant materials (Fig.2(b) and (d))* – Advances in micro-focus computed tomography hardware and software in the past decade provide a route to infer contact forces between compliant grains (e.g., [57]) at synchrotron [58] or laboratory settings [33] by using quantitative analysis of particle deformation (e.g., in rubber [57]). Imaging rates can approach 1 Hz but, as described in Sec. I, are now limited by maximum rotation rates at which centrifugal forces become significant. A gantry-based X-ray device eliminates the need for sample rotation and therefore eliminates centrifugal forces [33]; however, such a device will also have X-ray flux limitations that practically limit full-field imaging to about 1 Hz. Imaging rates of

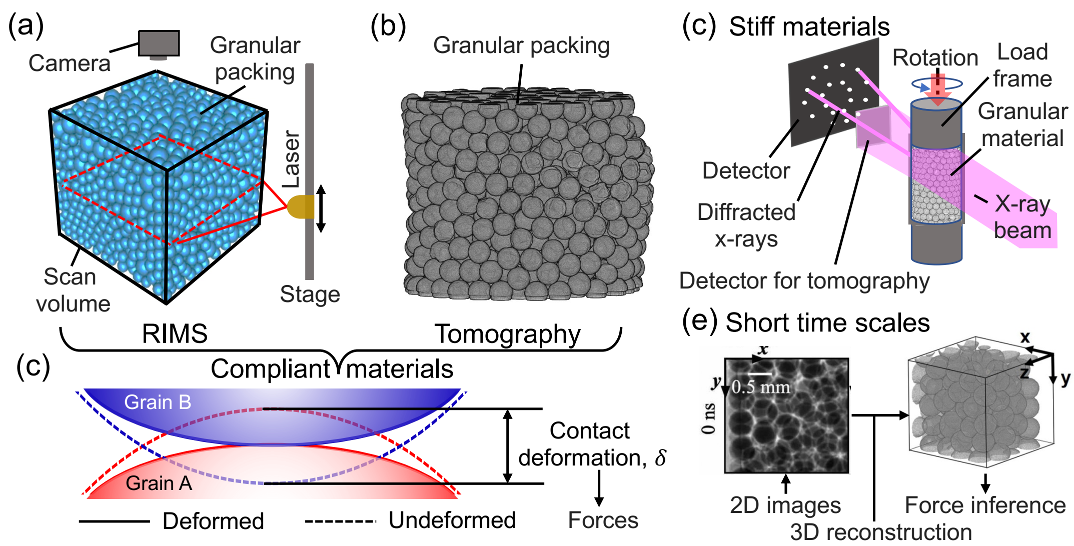

Figure 2: Possible approaches to dynamic force inference. (a) RIMS. (b) XRCT. (c) X-ray tomography and diffraction (d) Time-resolved 2D X-ray imaging with 3D reconstruction. (e) 2D imaging with 3D microstructure. (d) An illustration of how forces are inferred using RIMS and XRCT data for compliant particles. (e) adapted from [30] with permission.

about 1 Hz make X-ray tomography amenable to studies of stick-slip, non-local constitutive laws used to predict slow granular flows, and creep. As is the case for RIMS, X-ray tomography alone only allows inter-particle force measurements for compliant materials, and the timescale capabilities again limit access to the dynamics of force chain buckling events. Nevertheless, we envision that carefully designed experiments employing X-ray tomography – either rotation-based or gantry-based – may provide new and important insight into stick-slip, non-local constitutive laws, and creep in compliant materials.

3. *Time-resolved 3D X-ray imaging and diffraction for stiff materials (Fig.2(c))* – Rapid advances in 3D X-ray diffraction have, in the past five years, provided a means to study forces in stiff sand-like materials [29], shedding light on the role of forces in material failure, ultrasound transmission, and rearrangements [8, 9]. The technical approach to studying forces with X-ray imaging and diffraction involves using tomography for quantifying packing structure (particle shapes, sizes, and contacts) and diffraction for quantifying particle stress tensors. Measurements have historically been made in as little as about 10 minutes. Upgrades in X-ray flux and hardware at synchrotron facilities are likely to bring rates to as low as 1 Hz in the coming decades. Achieving rates below 1 Hz is impractical due to the need for sample rotation which will induce centrifugal forces to samples. Combined imaging and diffraction therefore will allow studies of stick-slip, non-local constitutive laws used to predict slow granular flows, and creep in stiff materials, but will not provide access to the subsecond dynamics of force chain buckling.

4. *Time-resolved 2D imaging with 3D reconstruction (Fig.2(e))* – Time-resolved 2D imaging, using laboratory-based X-ray systems or synchrotron-based X-ray phase contrast imaging, has emerged as a powerful tool for studying dynamic compaction and flow of granular materials [30, 59–61]. These imaging techniques provide only 2D images, but allow temporal image spacing as low as 153 ns at synchrotron facilities and 30 Hz in laboratory settings [30, 62]. While such imaging

is not 3D, novel algorithms have emerged in the last decade that enable reconstruction of 3D microstructures from 2D images, including flash X-ray tomography, projection-based digital volume correlation, and Fourier-space reconstruction methods [30,61,63–65]. We envision that these techniques, coupled with appropriate deformation-based force inference algorithms, can be used to study force chain dynamics at time scales relevant to all of the open challenges described in Sec. II. The challenge of using this approach for studying force chain dynamics is to develop robust algorithms for 3D microstructure reconstruction and force inference from 2D time-resolved images.

IV Discussion and conclusion

Time-resolved 3D force chain measurements at millisecond to second timescales have been challenging due to hardware and technical limitations. In this paper, we articulated five topics in which dynamic force chain evolution plays an important role across these timescales: stick-slip and intermittent flow; hypotheses underlying granular flow models; stress concentrations and hot spots during dynamic compaction; creep prior to catastrophic flow; force chain formation in discontinuous shear thickening. We also articulated four opportunities for making force chain measurements across a range of time scales, some or all of which should be possible within the next decade. These included: high-speed RIMS; time-resolved 3D X-ray imaging in compliant materials; time-resolved 3D X-ray imaging and diffraction for stiff materials; time-resolved 2D imaging with 3D reconstruction. The challenge to interested researchers in the granular materials community is to carefully develop experiments and robust algorithms that take advantage of technological developments for such force measurements in the coming decade.

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