SAND2016-2537C

Perturbation Decay Experiments on Granular Materials

Tracy J. Vogler
Sandia National Laboratories
7011 East Ave.
M.S. 9042
Livermore, CA 94550
tjvogle@sandia.gov

Masoud Behzadinasab, Rezwanur Rahman, and John Foster
Petroleum and Geosystems Engineering
The University of Texas at Austin
200 E. Dean Keeton St., Stop C0300
Austin, TX 78712

Abstract
Sakharov and co-workers [Sakharov et al., 1965] proposed an experiment 1965 in which a sinusoidal perturbation to a planar wave evolves as it travels through a sample. More recently, Liu et al. [Liu et al., 2005] utilized gas guns rather than explosives to drive the shock wave, resulting in better defined input conditions. Previous work involved study of solids such as aluminum and liquids such as water and mercury. Here, the approach is applied for the first time to granular materials. This experimental approach is attractive for granular materials as it probes phenomena in a different manner than, for example, planar shock experiments, and the length scales involved can be varied by changing the perturbation wavelength and amplitude. Continuum simulations as well as Lagrangian and Eulerian mesoscale models in which individual particles are resolved are utilized to study the evolution of the perturbation. It is found that the perturbation decay is delayed by material strength in the continuum simulations, but the compaction behavior does not strongly affect it. Effects of grain-scale phenomena such as particle fracture, interparticle friction, etc., are examined using the mesoscale models. Finally, initial experimental results for granular tungsten carbide are presented and compared to the simulations.

Keywords: granular materials, strength, shock wave, experimental methods, mesoscale modeling

Introduction

The perturbation decay experiment [Sakharov et al., 1965] was conceived as a means to study the stability of a propagating shock front and to probe the viscosity of the sample material at high pressures. Early experiments were explosively driven, but more recently impact from a two-stage gas gun [Liu et al., 2005] has been used. This has the advantage of providing well-posed initial conditions to the experiment. In the present study, the approach was modified to study granular materials. Initial experimental results suggest the approach has value and is primarily sensitive to the strength (deviatoric) behavior of the sample. Continuum and grain-scale (mesoscale) simulations have been used to understand the experiment better, revealing issues with the initial design.

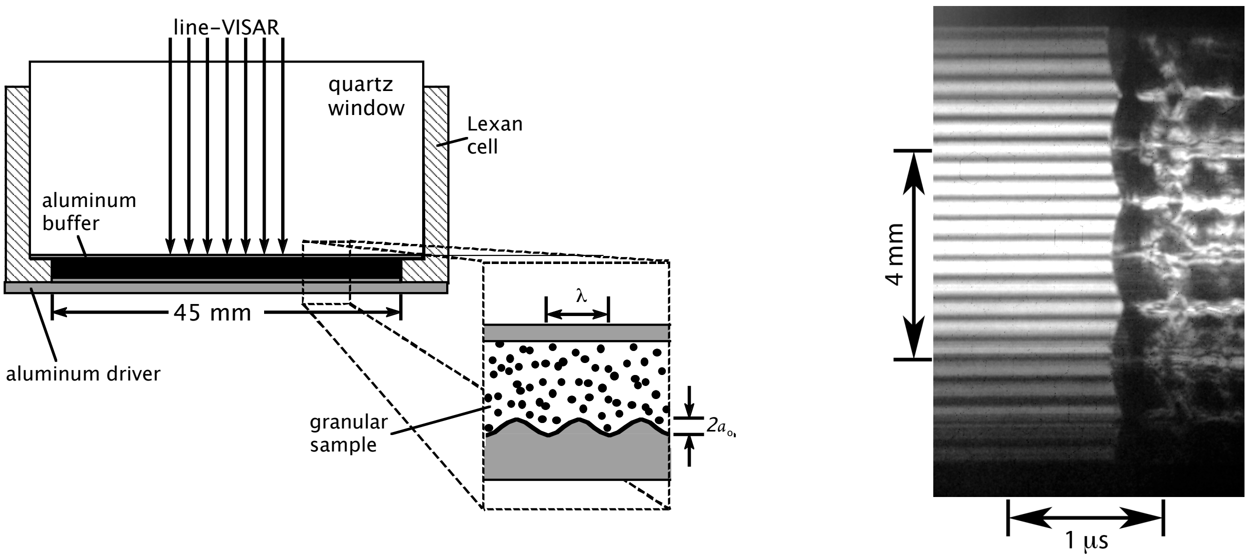
Experimental and Analysis Methods

The material studied in the initial experiments is the granular tungsten carbide (WC) studied previously [Vogler et al., 2007]. It has a blocky shape and was sieved to give grains in the range of 20-32 μm. An aluminum plate was launched using a single stage gas gun to a velocity of 874 m/s. It struck an aluminum driver plate into which was machined a sine wave of wavelength λ=2 mm and amplitude $2a_o$=0.5 mm as shown in Fig. 1a. The driver was backed by a sample of the granular WC, which was itself backed by a quartz window covered by a thin aluminum buffer. The sine wave in the driver plate generates a non-planar shock that evolves as it propagates in the sample.

Simulations of the experiments were conducted using the finite volume code CTH. Both continuum and mesoscale [Borg & Vogler, 2008] simulations were conducted. In addition, simulations utilizing a peridynamics [Silling, 2000] formulation were conducted to better understand the role of particle fracture and inter-particle friction.

Results

To evaluate the state of the wave after it propagates through the sample, a line-VISAR [Vogler et al., 2008] was used to measure the velocity history at the interface of the aluminum buffer and the quartz window. The measured velocity history is shown in Fig. 1b. The shock front is clearly non-planar, indicating that the initial perturbation has persisted even after traveling through over 2 mm of WC powder.



(a) (b)

Fig. 1 (a) Configuration of the perturbation decay experiment and (b) line-VISAR record from an experiment.

Results from continuum simulations are shown in Fig. 2. A region of high pressure is seen where the flow is converging near the "valley" in the driver, while a low pressure region is seen at the "peak." As the wave propagates, it decays in amplitude. However, the interface between the driver and sample (dashed line) remains essentially unchanged in shape after the initial shock passes.

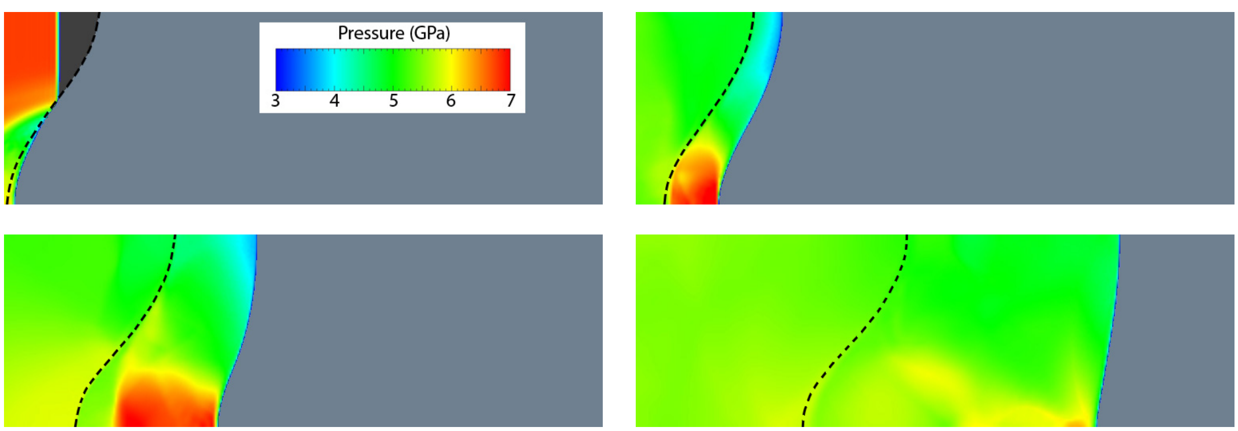


Fig. 2 Contours of pressure for a continuum simulation. The dashed line corresponds to the interface between the driver and the sample.

The continuum and mesoscale simulations suggest that the strength of the material rather than its compaction properties controls the decay of the perturbation. Somewhat surprisingly, two- and three-dimensional mesoscale simulations give quite similar results. However, the aluminum buffer between the sample and window is found to strongly effect the results, indicating that its thickness must be minimized.

Future Work

In order to address the issues found with the buffer, new experimental configurations are being explored. These new designs will also increase the data return from a single experiment so that the evolution of the perturbation can be traced out in a single experiment. Once the experimental configuration is finalized, additional experiments will be conducted to explore the sensitivity of the behavior to material properties (e.g. initial distention, grain size, particle morphology, compound) and experimental conditions (e.g. impact velocity, wavelength). Finally, preliminary simulations suggest that the addition of a second phase such as a soft metal or a liquid can significantly affect the response.

Acknowledgements
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

References
Borg, J. P., and Vogler, T. J. (2008). "Mesoscale calculations of the dynamic behavior of a granular ceramic," *International Journal of Solids and Structures* **45**, 1676-1696.
Liu, F.-S., Yang, M.-X., Liu, Q.-W., Chen, J.-X., and Jing, F.-Q. (2005). "Shear viscosity of aluminum under shock compression," *Chinese Physics Letters* **22**, 747-749.
Sakharov, A. D., Zaidel, R. M., Mineev, V. N., and Oleinik, A. G. (1965). "Experimental investigation of the stability of shock waves and the mechanical properties of substances at high pressures and temperatures," *Soviet Physics JETP* **9**, 1091-1094.
Silling, S. A. (2000). "Reformulation of elasticity theory for discontinuities and long-range forces," *Journal of the Mechanics and Physics of Solids* **48**, 175-209.
Vogler, T. J. (2015). "Shock wave perturbation decay in granular materials," *Journal of the Dynamic Behavior of Materials* **1**, 370-387.
Vogler, T. J., M. Y. Lee and D. E. Grady (2007). "Static and dynamic compaction of ceramic powders." *International Journal of Solids and Structures* **44**: 636-658.
Vogler, T. J., Trott, W. M., Reinhart, W. D., Alexander, C. S., Furnish, M. D., Knudson, M. D., and Chhabildas, L. C. (2008). "Using the line-VISAR to study multi-dimensional and meso-scale impact phenomena," *International Journal of Impact Engineering* **35**, 1435-1440.