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Surface instabilities in shock loaded granular media

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ABSTRACT

The initiation and growth of instabilities in granular materials loaded by air shock waves are investigated via shock-tube experiments and numerical calculations. Three types of granular media, dry sand, water-saturated sand and a granular solid comprising PTFE spheres were experimentally investigated by air shock loading slugs of these materials in a transparent shock tube. Under all shock pressures considered here, the free-standing dry sand slugs remained stable while the shock loaded surface of the water-saturated sand slug became unstable resulting in mixing of the shocked air and the granular material. By contrast, the PTFE slugs were stable at low pressures but displayed instabilities similar to the water-saturated sand slugs at higher shock pressures. The distal surfaces of the slugs remained stable under all conditions considered here. Eulerian fluid/solid interaction calculations, with the granular material modelled as a Drucker–Prager solid, reproduced the onset of the instabilities as seen in the experiments to a high level of accuracy. These calculations showed that the shock pressures to initiate instabilities increased with increasing material friction and decreasing yield strain. Moreover, the high Atwood number for this problem implied that fluid/solid interaction effects were small, and the initiation of the instability is adequately captured by directly applying a pressure on the slug surface. Lagrangian calculations with the directly applied pressures demonstrated that the instability was caused by spatial pressure gradients created by initial surface perturbations. Surface instabilities are also shown to exist in shock loaded rear-supported granular slugs: these experiments and calculations are used to infer the velocity that free-standing slugs need to acquire to initiate instabilities on their front surfaces. The results presented here, while in an idealised one-dimensional setting, provide physical understanding of the conditions required to initiate instabilities in a range of situations involving the explosive dispersion of particles.

1. Introduction

So-called jetting or fingering instabilities involving jets of particles are widely observed in phreatic volcanic eruptions, the detonation of landmines, shallow underwater explosions, and during thermobaric explosions. A common feature in all

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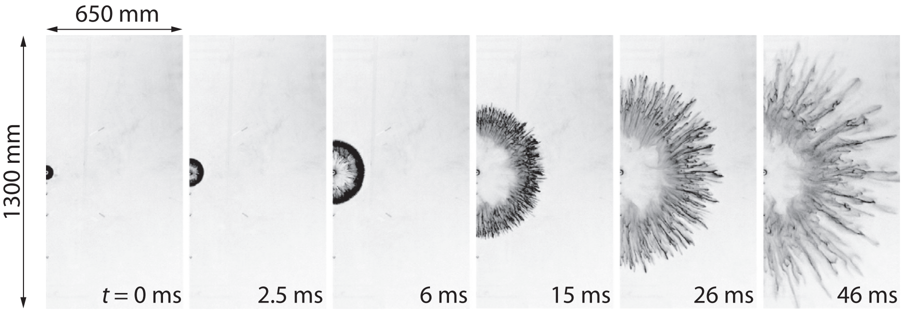

Fig. 1. Sequences of high-speed photographs showing the cylindrical explosive dispersion of a granular medium comprising flour particles ~15 µm in diameter (Rodriguez et al., 2014).

these examples is high dispersion speeds with particle jets acquiring velocities significantly higher than the average speed of the dispersal front. The understanding of the formation and nature of these jets is of interest not only from a scientific viewpoint but is also of practical interest. For example, volcanic ash jets significantly increase the area over which ash is dispersed while the granular jets in landmine explosions are a significant contributor to damage in the impacted structures.

There have been several recent efforts to perform controlled experiments (Frost and Zhang, 2006; Ritzel et al., 2007; Zhang et al., 2010) to understand the basic phenomenology of these jetting instabilities. Some of the key insights gained from these studies can be summarized as follows. The dispersion of the particles depends on the velocity acquired by the particles (Frost et al., 2010), which in turn is a function of the ratio of the particle to explosive mass. The experiments of Frost et al. (2010) showed that there exists a minimum velocity for the jetting instability to initiate while Keyner et al. (2017) demonstrated that the jet velocities can be 50% greater than that of the main dispersal front.

Experiments such as those of Keyner et al. (2017) and Liu et al. (2014) have carried been out in spherical and planar configurations, respectively wherein only the outer surface of the granular front was visible. Experiments have also been reported in a cylindrical configuration wherein both the expanding gas/granular medium and granular medium/atmospheric air interfaces are visible (Frost et al., 2012; Rodriguez et al., 2014). High-speed photographs of the cylindrical expansion of a granular medium comprising of ~15 µm diameter flour particles are reproduced in Fig. 1 (Rodriguez et al., 2014). These experiments show the formation of instabilities on both interfaces with the expanding gas/granular medium interface becoming unstable early in the time-history. Stable particle jets are seen after 2.5 ms at the expanding gas/particle interface and at 15 ms after the start of the expansion event on the granular medium/atmospheric interface surface. Frost et al. (2012) also reported that water saturation of the granular medium produces more jets compared to a dry granular medium. In fact, the dispersion of water without particles produces many more jets of liquid droplets (Cole, 1948) compared to dry or water-saturated granular media as noted by Frost et al. (2012).

The precise nature and causes of the instabilities responsible for jet formation at both interfaces remains a topic of active research. Ripley et al. (2012) focused attention on Richtmyer–Meshkov (Richtmyer, 1960) type instabilities (RMI), and demonstrated the formation of well-defined persistent jetting structures. However, the timescale for their formation was slow, and the surface instability did not propagate into the bulk. Milne et al. (2010) counted the number of jets and suggested a possible connection with dynamic fragmentation (Grady, 1982) while Frost et al. (2011) evaluated a compaction Reynolds number to connect expansion inertia to viscous dissipation. Discrete particle numerical calculations of Xu et al. (2013) suggest that particle jetting can be induced due to two sources: (i) the explosive gas forming jets induced by the shock wave propagating through the particle layers that the explosive gas is in contact with, and (ii) inelastic collisions between particles. However, multiphase numerical simulations by Zhang et al. (2013) suggest that the jets are connected to radial fractures in the fluid/granular medium. Thus, no consistent understanding of the physics of jet formation, and especially the influence of granular material properties (such as the influence of water) currently exists.

1.1. Scope of study

The aim of the study reported here is to develop a fundamental physical understanding of the mechanisms resulting in the formation of instabilities in shock loaded granular media. We thus report laboratory-scale shock tube experiments wherein the loading is well characterised and the initiation and growth of instabilities monitored in detail via high spatial and temporal resolution photography. Experiments are reported on both dry and water-saturated sand as well as a granular medium comprising PTFE spheres in order to span a wide range of granular material properties. These experiments are complimented with both Eulerian fluid/solid interaction simulations and Lagrangian direct pressure loading simulations. The simulations are used to construct maps that relate a stability criterion to loading conditions and material properties as well as to provide mechanistic insights into the origin of these instabilities.