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Shock-induced deformation in wetted particle beds

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Abstract. The high-strain-rate response of granular media has received considerable attention due to increasing interest in granular penetration. In the present study, we investigate the response of wetted packed particle beds under varying flyer plate-induced shock loadings. We investigate the critical conditions for the onset of particle deformation in systems of spherical macroscopic glass beads. Resulting particle deformations from the shock compression are characterized using microscopy as well as particle size analysis, and the effects of shock strength are compared. A fracturing response with a bimodal particle distribution is observed, with an increasing shift to the lower particle size range as shock loading is initially increased. As the transmitted shock pressure exceeds 1 GPa, a significant decrease in the mean particle size is observed.

1. Introduction

The response of packed dry particle beds to high-strain-rate loading has been well documented in the past [1-8]. The response of these systems to increasing stress loadings is dependent on the interparticle interactions and the force chain networks developed within the particle bed. In contrast, the response of wetted particle beds to similar dynamic loadings has received limited attention. As the liquid in the interstitial spaces of these wetted beds is capable of supporting stresses, the role of particle interactions on the global deformation of the bed is not well known. In the present study, wetted particle beds are subjected to various shock loadings to determine the role of the interstitial fluid on the compaction behaviour of the particles.

The response of granular media has received considerable attention due to its relevance in many fields including shock consolidation of powders for the formation of highly densified solids as well as modelling the dynamic response of soils. The modes of shock wave energy dissipation and the resulting changes in the microstructure of granular media during shock consolidation have been well reviewed [1, 2]. Various models have been developed, through the examination of different energy dissipation modes, which relate the shock energy required for consolidation to the initial powder morphology and material properties [1]. One such model relates the microkinetic energy, the plastic deformation energy, and the frictional energy dissipation modes to the shock strength required for the consolidation of different powders [2].

It is possible to obtain insight into the large-scale particle deformations which occur during shock consolidation through the use of Eulerian finite element numerical simulations [3, 4]. Gourdin proposed a numerical model employing surface heating and melting of particles during...
the consolidation process to predict the temperature evolution within a spherical powder [3]. Further treatment of non-spherical particles has been considered in the work of Benson, which examined the effects of particle morphology on the void collapse in a granular system [4].

Both wetted and dry soil beds have been studied extensively to aid in the modelling of geological phenomena (see review by Omidvar et al. [5]). The work of Whitman [6] examined soil dynamics pertaining to the effects of shock-loaded soils on underground structures. Whitman performed a detailed analysis on the deformation of the skeletal structure of the soil at varying stress loadings and identified the dominant mechanisms associated with the deformation. It has been seen that the shock wave strength and velocity vary greatly within a soil as it is saturated, with an onset of significant variation occurring around 20% saturation [7, 8].

A recent experimental investigation into the ballistic response of neat liquids, dilute suspensions, and dense suspensions of particles has shown that the penetration response varies significantly with the particle loading of the liquid [9]. The results showed that in neat liquids and dilute suspensions, the ballistic response was dictated primarily by mixture density. In the dense suspension, a more complex response was observed. At low impact velocities, the response appeared to be dominated by particle strength effects, however as the impact velocity was increased, this response underwent an asymptotic decay and converged to a density-driven response. It was hypothesized that this change in behaviour was due to an onset of particle deformation within the suspensions.

While particle deformation during shock loading of dry packed beds of particles is an accepted phenomenon, it is often not considered when wetted particle beds are dynamically loaded. This assumption is based on the considerable lubrication effects of the liquid, which participates in the mean stress transfer through the particle bed, resulting in lower magnitude force chaining. The present study seeks to verify the role of particle deformation in wetted packed particle beds, using well-defined loading conditions and particle recovery techniques.

2. Experimental Setup

The primary objective of the current work was to examine the response of wetted particle beds under various shock loadings. A steel recovery capsule was used to subject these wetted beds to one-dimensional shock loadings at pressures representative of those experienced in a ballistic impact. Wetted particle beds were held in a Teflon® cup in order to reduce the effects of reflected waves from the sample-capsule interface. A steel momentum trap was employed on the back face of the capsule to help maintain its post-impact structural integrity. A graphite gasket ring was used to ensure a hermetic seal such that no evaporation of the wetted bed would occur in the evacuated test section. A schematic of the recovery capsule is shown in figure 1.

The material used in this set of experiments was a low strength brittle ceramics, in particular #3 Ballotini® Impact glass beads (Potters Beads, LLC). The volume-weighted mean bead diameter of the initial beads was measured to be 700 μm using a Malvern Mastersizer 1000 with water as the dispersant. The particle and dispersant reflective indices used for the particle size analysis were 1.52 and 1.33 respectively. The Teflon® cup was filled with dry beads and a knife blade was used to ensure the sample was level with the top of the cup such that there would be no additional force chains formed within the sample prior to testing. The dry bed was wetted using distilled water until a meniscus was clearly seen above the sample, as shown in figure 2, ensuring that no gas would be trapped in the sample upon closing. The excess liquid was drained between the gasket-lid interface when closing the capsule.

A single stage light gas gun of 64 mm inner bore was used to launch a steel flyer plate, with 50 mm diameter and a thickness of 15 mm, at the recovery capsules containing the samples. A schematic of the gas gun assembly is shown in figure 3. The incident velocity of the steel projectile was varied between 150 m/s and 400 m/s, with the flyer plate velocity determined using a set of 3 induction gauges. Samples were impacted under near-vacuum conditions to prevent gas
cushioning of the flyer plate impact. The recovery capsules were offset from the launch tube to enable any remaining launch tube gases to expand prior to impact. The recovery capsules were collected post-experiment and opened to retrieve the shock-loaded samples. The samples were placed in an ethanol bath to aid in the separation of the liquid component. The remaining dry components were analysed using a Zeiss Axiovert 25 microscope with photographic capabilities. Further details on the experimental apparatus and technique can be found in [10].

3. Results and Discussion
Figure 4 shows microscope images of the initial glass beads, and of the glass beads after impacts with flyer velocities of 150, 250, and 397 m/s. The particle size analysis of the recovered samples which measured the percentage of each particle size by volume, q, is shown in figure 5. Shock
Hugoniot calculations of the transmitted pressure within the tested sample were carried out using a kinetic energy averaging method [11].

![Microscopy imagery](image)

**Figure 4.** Microscopy imagery of a) the initial particles, and the recovered particles impacted with a flyer plate at a velocity of b) 150 m/s, c) 250 m/s, and d) 397 m/s.

![Particle size analysis](image)

**Figure 5.** Particle size analysis of the initial glass beads and the post-impact glass beads.

It can be seen from figure 4(a) that the initial particles are fairly spherical in shape, with
a monomodal particle size distribution as shown in figure 5. When impacted with a flyer plate moving at 150 m/s, which corresponds to a pressure transmitted into the mixture of approximately 0.5 GPa, the emergence of a bimodal size distribution is observed with a decrease in the population of large particles and an increase in the population of small particles. This is indicative of the larger particles breaking up, as is confirmed in the microscopy results shown in figure 4(b). Increasing the impact velocity to 250 m/s, corresponding to a pressure of 0.9 GPa, one can see a further increase in the population of small particles and a decrease in the population of large particles. This shows that increasing the impact stress results in an increase in the fracturing of the original particles. Impacting the sample at 397 m/s, which corresponds to 1.5 GPa, leads to a shift of the original size distribution peak from 700 μm down to 200 μm, indicating nearly complete pulverization of the particles as shown in figure 4(d).

Previous work has shown that consolidation of dry particles occurs under similar shock loading pressures [3]. The interstitial liquid in the wetted bed precludes a void collapse mechanism during the shock compression of the system. The liquid is able to support some of the shock loading stresses, hence the dominant microstructural deformation mechanisms within the particle bed change to accommodate the different stress distribution. Due to the brittle nature of the glass beads used in this study, the change in the deformation mechanisms results in the fracturing of the particles. As shock strength and energy is increased, the particles undergo further fracturing resulting in a smaller average particle size.

4. Conclusions
An evaluation of the effect of varying the shock loading on wetted particle beds has been carried out. Impacted samples were successfully recovered and the post-test particle morphology and size distribution were characterized. In spite of the lack of voids in the initial mixture, some fracture of the brittle glass particles was observed at shock loadings of less than 1 GPa, producing a bimodal particle distribution. At a shock loading of 1.5 GPa, the particles were nearly completely pulverized.

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