Shock and release behaviour of sand

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Abstract. A considerable body of knowledge exists on the shock properties of dry sand. However, capturing the release properties has proven experimentally complex, and currently little information exists on the topic. The measured Hugoniot and release behaviour from a number of experiments is presented, carried out with the aim of furthering understanding of the fundamental physics behind the unloading of dry sand from a shocked state.

1. Introduction
The shock compaction of granular systems underpins our understanding of a wide range of situations, such as granular flows [1] and impacts between celestial bodies [2]. While research continues to enhance our understanding of these and other granular phenomena, a complete theory of the underlying physics remains elusive [3]. Therefore, phenomenological models usually require extensive experimental data in order to accurately predict the response of complex systems. Typically, a particular granular material is studied under specific conditions in order to form a material model. Sands and other soils are one key area of interest due to their ubiquity in nature, and to this end a substantial body of work has been performed on a range of such materials. One crucial aspect of research which has been lacking from the literature, however, is an understanding of how the compacted material releases from a shock compressed state. Release governs the behaviour of the sample at boundaries with lower impedance materials, and is therefore a vital aspect of numerical models when applied to complex, "real world" situations. In this paper, we present a simple method by which shock-release information may be obtained for granular materials. A summary of the results presented here can also be found in [4].

One-dimensional plate impact geometries are the typical method of studying shock Hugoniot responses of granular systems, and in such situations pressures of up to several GPa may be obtained in silica-based materials, as in [5-7]. Brown et al. collated results of a number of studies on dry sands [8], which showed similar trends but with significant absolute differences. This variation in results was attributed to differences in initial densities, grain sizes and experimental techniques, although the exact mechanism is not currently well understood. Neal et al. [9] have begun to address these issues by focusing on simpler systems of quasi-monodisperse spheres. Studies using laser interferometry have identified re-shocked states produced by reflecting shocks in sand from a higher impedance material [8], although to our knowledge no data has previously been published of release due to reflection from a boundary with a material with lower impedance than sand.
2. Experimental

A series of one-dimensional experiments were performed using the Cambridge plate impact facility [10], in order to probe the shocked and released states of dry sand. The apparatus comprises a 50.8 mm (2 inch) bore single-stage light gas gun, which is able to launch flyer plates at velocities ranging from 100 to 1100 m s\(^{-1}\). A schematic of the plate impact cell used in these experiments, adapted from those in [11], is shown in figure 1. The cell constrains the sand in a bed between Poly(methyl methacrylate) (PMMA) plates and an aluminium annulus, with the sand bed depth restricted to 3 mm to ensure that the diagnostics remain in regions of one dimensional strain. A manganin stress gauge (Micro-measurements LM-SS-125CH-048) is embedded using epoxy resin between the two front plates. The rear plate contains a 10 mm diameter hole, fronted by a 25 µm thick copper shim, onto which the laser from a Photonic Doppler Velocimeter (PDV) is aimed. Some of the Hugoniot results presented in this paper used an earlier design, where a second stress gauge package was used behind the sand in place of the laser, and no release data were acquired.

![Figure 1. Schematic showing a section through the “sand-cell” used for one dimensional plate impact experiments, where the sand is encased between PMMA plates. A stress gauge and laser velocimeter record shock propagation time and free surface velocity, enabling simultaneous characterisation of the shock Hugoniot and release to vacuum.](image)

Fine quarry sand, the particle size distribution for which is given in figure 2, was used in the experiments. The sand was passed through an 850 µm sieve to remove unrepresentatively large grains, baked for 24 hours at 120 °C to remove residual moisture, and used to fill the cells to a "poured" density of between 1.38 and 1.45 g cm\(^{-3}\). The cells were impacted with 10 mm thick flyers at velocities ranging from 493 to 1089 m s\(^{-1}\). Both copper and PMMA flyer plates were used, to increase the range of impact stresses tested.

The stress gauge trace shows an abrupt pressure rise indicating the point of shock arrival. The recorded stress was not used in the analysis, as it was determined that the impact stress could be more accurately calculated from the known Hugoniots of the flyer material and PMMA target.

At the rear of the sand bed, the shock passes into the copper shim. Since the copper is 25 µm thick, it will “ring-up” over 5 to 10 reverberations [12], taking around 50 ns, which is substantially faster than the velocity rise time in these experiments. As such, the free surface velocity of the copper will equilibrate quickly to that of the sand, thus providing information about the release state of the latter. There is no evidence of the velocity trace broadening or splitting, and repeat experiments give largely similar results, indicating that the copper has not been perforated or otherwise deformed by the sand.
Additionally, as the shock impedance of copper is higher than that of sand (even when fully compacted), the two materials remain in contact throughout [12].

An example of the PDV trace is given in figure 3, following the copper free surface velocity. This velocity rises sharply, before reaching a plateau of near-constant velocity for several microseconds. The combination of stress gauge and PDV give shock time-of-flight, enabling the shock velocity in the material to be obtained.

Figure 2. The sand particle size distribution (as measured in a Malvern Mastersizer) after being passed through an 850 µm sieve. The sand is weakly graded, and follows a roughly log-normal distribution with upper and lower quartiles by volume of approximately 250 and 125 µm respectively. The lack of clay component means that the sand may be assumed to be cohesionless.

3. Results

Once the shock velocity had been obtained, impedance matching was applied to determine the sand Hugoniot. The Rayleigh loading line in the sand may be determined from shock velocity and initial density, and interacts with the front anvil release at the Hugoniot stress. Here, the PMMA release has been approximated by the Hugoniot, which is a standard assumption [13]. Applying the Rankine-Hugoniot equations then allows the remaining parameters to be calculated, as in [14]. Figure 4 shows the Hugoniot for dry sand in particle and shock velocity space, while figure 5 displays both the shocked and released states in stress and particle velocity space. In each experiment, the material is initially loaded to one of the states given by the Hugoniot points (black crosses). The release states are shown by the red circles, assumed to be at zero pressure. In the cell, the release wave propagates backwards into the sand bed (in the opposite direction to the initial shock propagation). To give the release state expected for a forward moving release state, in line with convention, the free surface velocity points have been reflected about their respective shocked particle velocity points.

It can be seen qualitatively that there is significant hysteresis due to irreversible compaction, with the final particle velocity in the released state being substantially different from the zero that would be expected for a fully elastic release. This method, of course, gives only the two end points of the release path, and no further information. In the figures we have shown a linear release path, which we justified by a subsidiary set of experiments (using a different technique that gave additional information) performed on a very weakly bonded sandstone, the results of which are given in figure 6. The stone

Figure 3. Typical raw PDV spectrogram trace from one of the experiments. The velocity can be seen to rise rapidly at the initial shock arrival, before reaching a steady plateau for several microseconds. Beyond this point reflected shocks and other phenomena break the one-dimensional requirement for our analysis.
has no discernible yield strength in shock measurements and a porosity of 18 \%, and is therefore an approximation to free-running sand, and may be studied as an analogous system.

**Figure 4.** Hugoniot of the sand, plotted in shock and particle velocity space. Within the experimental range, the Hugoniot follows a linear relationship. Note that several measurements were performed using a rear manganin stress gauge (with no associated release) instead of the copper shim method.

**Figure 5.** Hugoniot (black crosses) and release states (red circles) for sand. Significant non-elastic behaviour is seen with the hysteresis present in the shock-release cycle. A straight line is drawn through the release path, justified through the similarity between sand and sandstone (shown in figure 6).

**Figure 6.** Hugoniot and release data for a weakly bonded sandstone. The ring-down method applied here, which was unsuccessful on the cohesionless sand, indicates a linear release path. Due to the similarity between the two materials, a similar path may be assumed for sand.

**Figure 7.** Compaction plot showing the Hugoniot and release points, converted into pressure and specific volume space. There is substantial compaction during shock compression which is not recovered on release, and release paths follow a similar gradient to the quartz Hugoniot.
In the sandstone experiment a reverberation method was used, whereby the sandstone was impacted in a reverse ballistic configuration into a copper witness plate. This plate was monitored by a VISAR (Velocity Interferometer System for Any Reflector) laser interferometer [12]. The ring down in stress on the copper plate after impact, measured as a ring up in free surface velocity, serves to describe the release state in the sandstone at several stress levels. The data obtained by this method shows a straight line release path from Hugoniot to final state, with no significant associated structure. Due to the similarity between the sand and sandstone, this result provides strong support for our assumption of a straight line joining shock and final release states.

4. Discussion & Conclusions
Considering the structure of the shocked granular material allows us to gain insight into the general form of the release waves. In a perfectly elastic material, a complete recovery of the original state is expected following a cycle of shock and release. In the sand, however, the released state is significantly different from that of the un-shocked sand, and so the cycle is far from elastic. Under loading, grains may compress, rearrange and fracture. Of these three processes, only the first may be considered an elastic process, and only if stresses do not exceed the Hugoniot Elastic Limit (HEL). Rearrangement and fracture of grains involves energy transfer to heat, bond breakage and surface production, and is to first approximation entirely inelastic. It is therefore likely that the dominant process in the release is relaxation or re-assertion of the quartz, as opposed to any involvement of the granular mesoscopic characteristics of the sample material. Figure 7 shows the release points converted into pressure and specific volume space. Under shock loading there is substantial irreversible compaction, consistent with grain fracture and rearrangement as mentioned above. The shocked density approaches but never reaches that of fully dense quartz, as is expected of a porous Hugoniot. The quartz release (approximated below the HEL by its Hugoniot) tracks parallel to that of the sand, which is consistent with the unloading of compressed grains being the dominant release process. The release wave velocity may be obtained by division of the gradient with sand density at the shocked state, and our data yield velocities in the range of 2.9 to 4.7 km s$^{-1}$. These are comparable to the predictions in [15], which are based on a pressure-dependence of bulk sound speed. Some spread is apparent in the release measurement slopes, although we believe this is likely to be due to variations between granular samples rather than any stress-dependence on release velocity.

In conclusion, we have developed a technique by which release measurements of low-impedance granular materials may be obtained with relative simplicity. While the data presented is for a typical sand, our technique may be widely applicable to other granular systems. Of particular note, we expect that the structural properties of the material will be important in determining release, and quite different behaviour may be found for systems with smaller particles such as clays or silts, where the material displays some cohesion.

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