Title: Deformation and Flow in Granular System from Impact and Blast Loading (U)


Intended for: 31st International Workshop on Physics of High Energy Density in Matter - (PRIOR collaboration)
DETAILS DESCRIPTION OF THE EXPERIMENT OR ACTIVITY
(Describe the science of engineering research being addressed, importance, and a description of how this experiment campaign will contribute to the progress of this research.)

Deformation and Flow in Granular Systems from Impact and Blast Loading
Update January 2011

Some parts for these experiments, including boxes for holding the sand, have been constructed. Additionally, well characterized sand from Eglin Air Force Base, known as Eglin sand, has been shipped to Los Alamos. Additional calculations simulating drive pressures using CTH and timing calculations are needed. Dynamic experiments have been scheduled for July 2011.

Shaped Charge Jet Perforation

The initial proposal intended to utilize the 40mm powder gun at LANSCE to drive solid objects into sand beds. Since the gun will be unavailable until perhaps FY2012, this series of penetration experiments will be conducted using shaped charge jets to establish the concept of measuring granular flow with Proton Radiography. A description of the experiments follows:

- A sparse layer of steel particles of similar size to the sand particles will be arranged in a plane centered around the detonator and normal to the field of view
- A Viper shaped charge (Fig. 1.) will be fired into the sand bed from above, aligned so it penetrates the layer of steel particles
- This series will need the –I lens system to capture the movement of this beaded layer of particles as the expansion process takes place
- A DICC (Digital Image Cross Correlation) algorithm will be used to measure the displacement on an image-by-image basis thus producing a planar displacement field within the bed of sand

This part of the investigation will focus on analyzing the penetration of a shaped charge jet penetration on sands of differing packing densities.
Shockwave Densification Analysis

Research into the shock densification of sand has previously focused on measuring pressure and particle velocity to infer densification using the Rankine-Hugoniot Jump Conditions. Due to its heterogeneous nature and porous composition, the inferred densification has come into question. There has been no attempt to transiently measure density within a sand bed undergoing shock transition. This series of experiments aims to measure density during shock transition through a bed of sand to determine the relation between it and particle velocity of the shocked material.

It is likely that the experiment will consist of the following:

- An explosive plane wave lens will be used to drive a Taylor-wave into a bed of sand
- The 3X magnifier will be used to gain high-resolution density measurements across the shock-wave, providing in situ shock wave profile measurements
- Multiple point VISAR readings will measure free-surface velocity at different longitudinal points throughout the bed that will be compared to direct density measurements from the radiographs
- Three shots will be completed using sand with differing initial densities

Spherical Wave and Flow Analysis

After shock densification during a buried explosion, gaseous products continue to expand. This expansion process causes flow within the granular bed and little is known about the mechanisms that occur during this process.

The experiment will consist of the following:

- A small explosive charge, such as a detonator, will be placed within a bed of sand
- A sparse layer of steel particles of similar size to the sand particles will be arranged in a plane centered around the detonator and normal to the field of view
• The -I lens system will be used to capture the movement of this beaded layer of particles as the expansion process takes place
• A DICC (Digital Image Cross Correlation) algorithm will be used to measure the displacement on an image-by-image basis thus producing a planar displacement field within the bed of sand

This experimental series will be conducted on beds of sand of differing packing densities and be complemented by the shock densification analysis utilizing the 3x magnifier. Accurate displacement and therefore velocity field mapping will be achieved to potentially highlight the mechanisms that occur during underground explosions.

**Future Work**

In stress transmission through granular materials there are many theoretical models which predict a low-stress precursor wave leading, by some time-distance, any higher-stress states. This wave has been observed experimentally using sensitive stress measurement techniques, however, it is unclear what the process of transmission is; rival theories exist but some are based on rapid particle rearrangement. Proton radiography has the necessary sensitivity, spatial and temporal resolution to address this issue and provide a much needed insight. Recent experiments at the Institute of Shock Physics at Imperial College, London, indicate the presence of a precursor wave which decays with input stress and disperses with bed thickness. It is theorized that the magnitude of the densification of this precursor wave is due in part to the partial rearrangement of the grains as they are driven by the subsequent shockwave.

Shock physics models predict the existence of such a wavelet if the material has strength. Most porous materials lack strength, however it is been shown that sand does have strength in compression and torsion; yet in tension, sand's material strength is negligible. In this way is it very much like most building material, for example, a brick wall, where the compressive strength is several orders of magnitude greater than the tensile. Bragov\(^2\) used plate impact and Kolsky (Split-Hopkinson Pressure Bar) experiments to obtain properties on confined sand over a range of strain rates. These experiments showed that the behavior of confined quartz sand can be explained using a friction-based Mohr-Coloumb response type approach which is used to indicate torsional strength. Proud\(^3\) showed that behavior changes smoothly over strain rates when sand is crushed. They argue that multiple processes such as particle movement at low stresses and fracture at high stresses are happening at the same time and balance behavior changes with pressure. Finally it has been shown that rate is important in the movement at a mesoscale such that the movement pattern at low rates is different to that at high rates.\(^4\) These results taken together indicate that (a) although sand is considered porous, sand had compressive and lateral material strength, (b) there are multiple processes occurring which are yet to be completely understood (c) the balance/contribution of these processes changes with strain rate and (d) this change is also seen in the material movement and (e) support the existence of a precursor wave.

Precursor waves have been observed in previous experiments, matching some theoretical predictions. However, the underlying mechanisms producing the precursor waves are not well understood. It is expected that a sufficiently detailed elucidation of the wave properties, such as velocity, density change and profile, will help theorists determine the underlying mechanisms. Thus, in addition to continuing the current set of experiments, we propose a new experimental series to use Proton Radiography to resolve this precursor wave and determine the mechanisms producing the wave, such as motion or densification.
FY 2011 Proposal

Deformation and Flow in Granular System from Impact and Blast Loading

Abstract
The study of particulate, sand-like materials has a wide scientific and applied relevance. The mechanical response of the material to external stimulus is complex with particle movement, friction, fracture and compaction playing major roles. The fundamental physics of many of these processes are not understood. Similarly, there are issues as to what physical model is appropriate for which length scale of system and which physical parameters dominate a given range of strain rates. The energy absorbing properties of porous media, however, is widely known and used in blast and ballistic mitigation in the commercial and military sectors.

1. Experimental Programme

Several groups have produced high-quality research, in the static and quasi-static regimes [1-4]. This proposal will complement this research by extending the range of strain rates and by developing new techniques to produce a robust set of data suitable for modelling and for comparing different theoretical predictions. Proton radiography adds the ability to produce multiple short-exposure, high-resolution images, which can then be cross-correlated to show the internal structure and flow within the granular bed. This represents a unique opportunity to study the physical phenomena and parameters in depth - flow fields, local densification and the effect of grain size and porosity.

Beds of quartz sand particles will be subjected to loading, images captured during the impact process and image correlation techniques used to study the displacement within the system and the extent of stress transmission through the bed. Both mono- and multi-modal (polydisperse) distributions of particle sizes will be studied. The response of the system will be tracked by analysing the images using image cross-correlation techniques to examine the displacement, both translational and rotational, movements within a bed. The technique is based on a seeded layer in the target, a technique pioneered by this group [5].

The load will be applied either by using 2 shapes of either plate, conic, triangular or spherical penetrators launched from a gun or penetrator launcher. The images will be captured during the impact and penetration process. The material of the impactor will be of sufficient hardness and rigidity to avoid bending or significant erosion by the sand. The deformation field produced by the impactor will show the effect of stress transmission, compaction and, most importantly material flow. In a second set of experiments a small explosive charge will be placed within the granular bed and detonated. The will produce both stress and high-pressure product gas which will percolate in the bed and so providing a significant additional effect compared to the impactor system. The penetrator size may be varied from that of a few particles in diameter to a size approximating the particle bed, similarly a range of explosive charges will be used to produce a range of impact velocities. Experiments will be conducted over a range of impact velocities as previous research has shown the response, compaction and flow, varies greatly with stress level [6].

Other factors such as the correlation of the displacement maps with force chains will be investigated. Given the fragility of the particles it is expected that significant force chain redistribution will correspond to small movements within the bed.
2. Proton Radiography details

The pRad experiment series will consist of 8-12 shots using the powder gun driver or a penetrator launcher, and the 3X magnifier lens. The parameters to be varied will consist of the geometry of the penetrator, including its face's shape and its diameter, and the impact velocity. The possible impactor face shapes may include flat, conic, triangular or spherical. The impactor diameters will be 5 mm and 20 mm. A range of impact velocities will be explored from 500 m/s to 1000 m/s. The requested number of shots thus, two chosen shapes for two diameters with up to three impact velocities, with a maximum possibility of 12 shots.

For every shot, the same target design will be used: a polyethylene cube, 50 mm on a side, packed full of sand. The target walls will be 1/8 inch Lucite or similar, except for the side which the impactor hits, which will be as thin as possible.

All the shots will require the full suite of pRad diagnostics, including at least 19 high resolution images using the cameras at image location 1, PDV velocimetry to measure the speed of the impactor prior to impact, and voltage pins to trigger the radiography system. Typical proton pulse lengths will be 50 to 100 ns, with 20 to 40 pulses in the chain separated by about 350 ns.

3. Data Analysis and Method

Analysis using correlation schemes, as shown schematically in figure 1 has been optimised to deal with granular systems. The technique has been applied to polyester, cement, sand and glass materials [7-10]. This correlation algorithm was developed in collaboration with Sjödahl [11,12]. The results of image processing and the resulting displacement map are illustrated in the two scenarios shown in figure 2. The experimental process requires a reference image, taken before the impact and an image taken during the impact process experiment. A layer of random radio-opaque particles are used to produce the speckle pattern to ensure that the array is a random pattern with no two areas being alike. A sub-image is taken from the reference image and a similar, but smaller, region is taken from the deformed image. Moving the deformed sub-image pixel by pixel across the reference sub-image, and calculating a correlation value at each step, creates a correlation surface. A clear peak in the correlation stands out from the background noise when pattern overlap occurs. By locating this peak the displacement in the deformed sub-image relative to the reference sub-image has been calculated. The location of the correlation peak can be obtained to sub-pixel accuracy and can be as good as 0.001 pixels of displacement.

Figure 1. The stages of image processing
Figure 2. Example of displacement field around (a) displacement copper shaped charge jet moving at 7 km s$^{-1}$ through cement target, note – the quiver arrows are 10x magnification (b) flow pattern around a bullet fired into a cube of sand at 500 m s$^{-1}$.

Overall

The experimental techniques outlined above have been developed over a number of years. They have been applied over a range of systems including some porous and granular. Some novel experimental development will be required while other systems will need to be optimised, particularly the statistical analysis of the images of force chains.

The programme outlined here is to apply a range of techniques in a systematic fashion to granular systems over a wide range of rates and with close involvement of the theoretical and modelling communities.

Contribution made by UK-based researchers – Academic Input

The UK team would supply all sample materials and fabricate targets. In collaboration with pRad collaboration members the impactors would be jointly designed, then fabricated in the UK. The UK team includes a doctoral student who is currently funded to research the dynamic properties of Granular Materials who is in the early stages of his programme and who would benefit greatly from these results. All travel and subsistence costs would be met by existing funding within the UK team.

References

7. Bragov A.M., Lomunov A.K., Sergeichev I.V., Proud W., Tsembali K. and Church P. (2005) “A method for determining the main mechanical properties of soft soils at high strain rates (10$^{-1}$-10$^{5}$ s$^{-1}$) and load amplitudes up to several gigapascals” Tech. Phys. Letts 31 530-531