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Blast testing of explosive charges buried in frozen soil

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Abstract

Historically, most testing with shallow buried charges has focussed on soils which are predominantly quartz (silica) based. Particle size, moisture content and density have been previously investigated to ascertain the geotechnical parameters that govern the development of impulsive output. This has shown that in order of importance, moisture content, density and particle size drive the total impulse delivered. However, particle size does have a dramatic impact on the localised loading delivered to a target.

The work in this paper presents testing done with frozen quartz sands, to investigate the difference that freezing the soil has on both the localised loading and the total impulses recorded using the University of Sheffield's Characterisation of Blast Loading (CoBL) apparatus. Frozen soils have significantly different material properties, acting as a solid material instead of a cohesionless granular material.

A process was developed for the preparation and blast testing of frozen soil samples and the results were then compared with the well-established Leighton Buzzard uniform sand to isolate the effect of freezing on the soil.

Introduction

Extensive research into the influence of soil conditions on the loading caused by a shallow buried charge has been carried out by numerous research teams. Westine et al. hypothesised that in the case of a buried charge, the loading is primarily impulsive due to the material striking the target rather than being due to shock wave loading [1]. This finding was further confirmed by Ergott et al. [2] affirming the importance of understanding the mechanics of the soil ejecta.

The Westine model [1] allows for a first-order approximation of the impulse from a buried charge to be calculated; however, the soil is categorised solely on its bulk density. More recent work has investigated additional parameters, including moisture content [3][4][5][6][7], void ratio and permeability [2][6][8][9], particle size distribution [2][6][10][11] and soil mineralogy (quartz [2][6][7][11], clays [2][3][6], alluvial [7][11] and carbonate soils [12]).

One significant absence from the literature is the understanding of the effect of frozen ground has on the output from a shallow buried charge. Frozen ground has been extensively studied and understood for the purposes of construction [13]. In this field, methods exist for the preparation of soil samples for lab scale testing [14]. However, these techniques are not applicable to the scale required for blast testing and so a new methodology for sample preparation was developed.

Test methodology

The CoBL test rig was fabricated in 2013 and has been widely reported [6][12][13][14][15]. The component parts are a stiff reaction frame constructed from steel and fibre reinforced concrete, into which 50 mm thick steel acceptor plates are cast at the underside of the concrete beam. Load cells are bolted between the underside of the acceptor plate and a 100 mm thick 1400 mm diameter mild steel target plate. The target plate has an arrangement of holes that accept 10 mm diameter 3 m long Hopkinson pressure bars. On top of the concrete beam, a Hopkinson pressure bar support frame is bolted such that bars are suspended and vertically aligned above soil bins. A schematic representation of the arrangement is included in Figure 1(left), and a photo of the test apparatus with a soil bin in situ below the target is in Figure 1(right).

Each of the 17 bars used in the apparatus has two strain gauges attached to it in a balanced Wheatstone bridge configuration allowing the strain to be recorded by a high-speed USB oscilloscope[1].

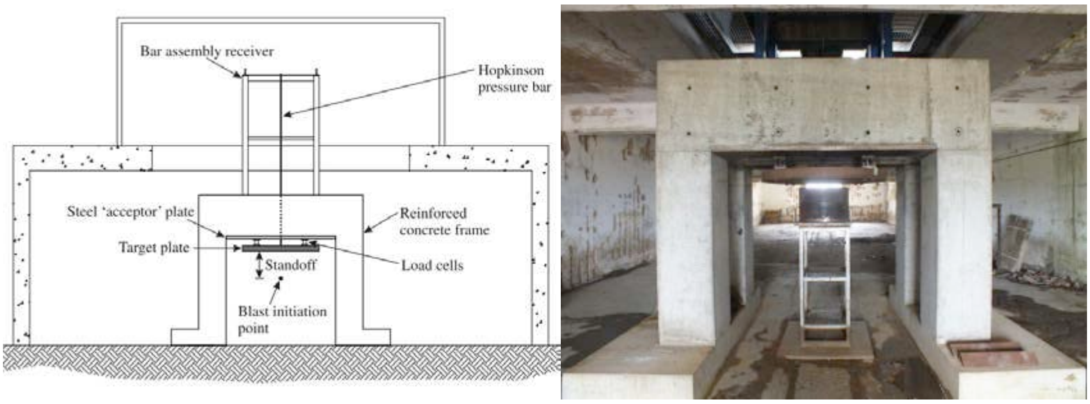

Figure 1. Left: Schematic of the CoBL trials apparatus; Right: Photograph of the CoBL trials apparatus

Frozen soil sample preparation

Previous work of Fay et al. [13], Clarke et al. [6][14][15] and Lodge et al. [12] developed a highly consistent process for the preparation of soil samples for buried charge testing. Their process has been modified for this testing to account for the fact the soil is frozen prior to testing. The new process is as below, which constructs soil samples in two parts. The method outlined below is the process for a fully frozen bin, with the charge placement elements pictured in Figure 2. For partially frozen bins, freezing is achieved by only freezing the top or bottom section of the sample.

Prior to testing

1. Prepare soil bin to defined geotechnical conditions as per previous work
2. Prepare 80mm thick soil discs to defined geotechnical conditions to form the 'lid' of the frozen soil sample (25kg at 80mm thick gives a bulk density of 1.6kg/m^3)
3. Rapidly freeze the soil container and disc in a refrigerated ISO container at approximately -25°C

On the day of testing

4. Screed off the top 50mm of soil from the bin
5. Place the 80mm thick disc in the recess and screed off till level
6. Once correctly sized, remove top disc to place charge
7. Cut a channel in the base for the detonator and breakwire leads to sit within
8. Cut a recess in the underside of the disc for the charge to sit in
9. Place the charge in the base piece and backfill with sand burying the wires
10. Place the top piece on top of the charge and soil
11. Install the soil bin in the test rig and proceed with the test

To confirm that the two part approach to creating a soil sample was valid, one test was conducted with a soil sample prepared in a cardboard tube that was removed prior to testing. An image of this arrangement is included in the bottom right of Figure 2. The two layers can be seen as the top layer was made with a different batch of sand that was a slightly different colour. Results from this test are discussed below.

[1]Handyscope HS4 https://www.tiepie.com/en/usb-oscilloscope/handyscope-hs4

Test configuration

During the testing, wherever possible, all parameters other than the variable being investigated were held constant and in line with previous work to allow comparisons to be made with existing data. Table 1 details the values that were held constant throughout the testing.

For this work, four different test configurations were used with three repeat tests of each. The four configurations are detailed below in Table 2 and Figure 3. These aimed to investigate the effects of the ground freezing and represented three different potential arrangements frozen and unfrozen soil. A final series was conducted to compare ice to previous water tests

Figure 2. Images showing the different stages of burying a charge in a frozen soil bin. The top two show the channel dug out below the charge for the detonator and leads, the bottom left image shows the top ice slab with a former to create the void for the charge and the bottom right shows a frozen soil sample removed from the cardboard former prior to testing.

Item	Value
Charge mass	78g
Charge type	PE4
Charge dimensions	3:1 cylinder (57mm diameter, 19mm depth)
Charge case	3mm thick 3D printed open topped case
Charge position	Central in bin with detonator below
Stand-off distance	140mm sand surface to CoBL target plate
Burial depth	28mm to charge surface, 37.5 to charge centre
Nominal LB sand bulk density	1600 ± 50 kg/m^3
Nominal LB moisture content	5.0% ± 0.1%
Trigger method	Break wire embedded inside the charge, looped round the detonator

Table 1. Values held constant throughout the testing to ensure consistency and comparability with previous work.

Test Series	Sand	Description
Frozen Full	LB	Full frozen sand
Frozen Bottom	LB	Sand frozen below base of charge representing permafrost
Frozen Top	LB	Sand frozen above base of charge representing a UK type winter
Ice	N/A	Water ice
LB5%	LB	5% moisture content LB – Clarke et al [15]
Water	LB	Water - Clarke et al [15]

Table 2. Details of the six different test series and labelling used for historic data comparisons.

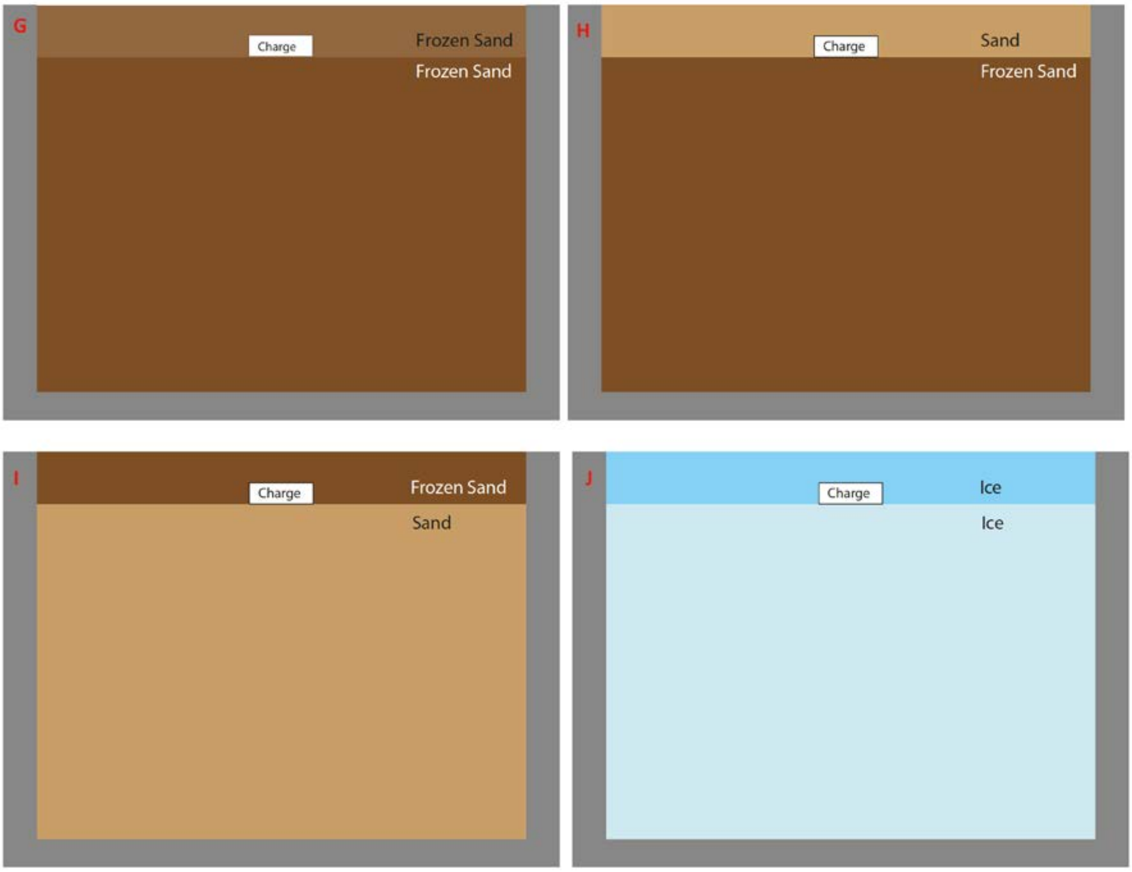

Figure 3. Visual representation of the four new test series reported on in this work.

Results

Frozen soil sample construction verification

As discussed above, one test was conducted using a fully frozen soil sample without the confining bin to allow high-speed video footage to be taken of the sample to assess the breakup. Figure 4 shows four frames from this test covering the period up to 800µs, during which there is no discernible breakup of the soil sample. From 428µs the reflected shockwave from the target plate can be seen traveling down through the air beside the sample which is still undisturbed. This indicates that the inertial confinement offered by the frozen soil is sufficient to contain it during the time over which we are measuring the pressure. For comparison, the loading observed on the array of Hopkinson bars is typically within the first 300 µs.

Figure 5 shows that post testing the whole sample has been broken up into loose sand with no clumps of frozen sand remaining. This further demonstrates that the material is inertially confined during the testing and the two-part construction does not lead to the top slab of sand being projected into the test rig.

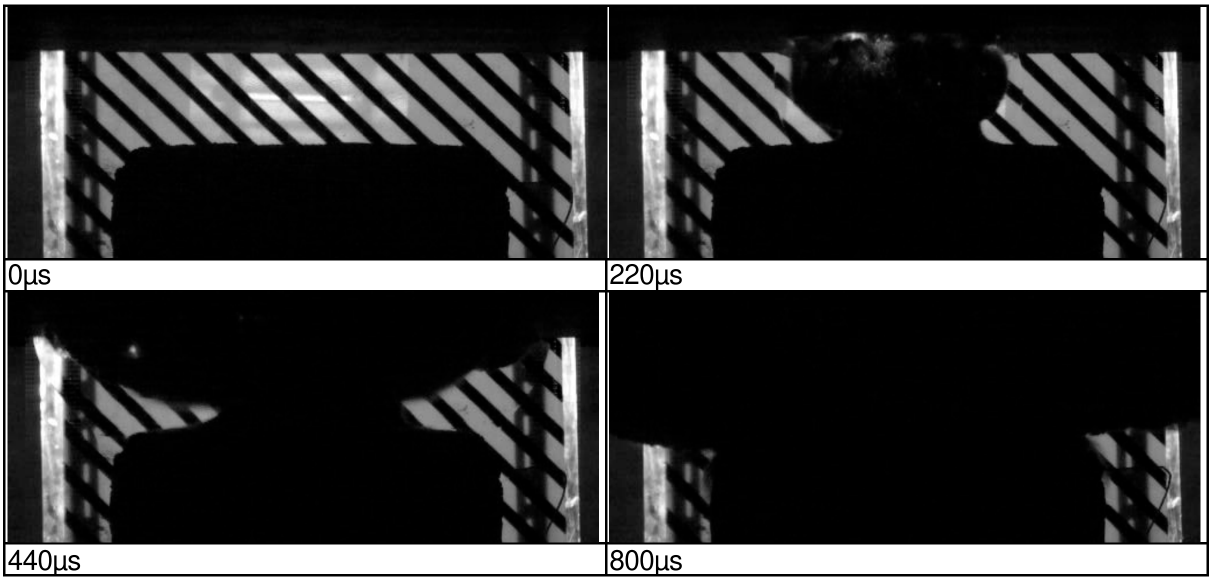

Figure 4. Images from high speed video of the unconfined soil test showing that there is no discernible lateral breakup of the sample over the period of interest. The 800µs image shows the detonation products that have expanded from the top surface round the sides.

Figure 5. Post-test photos showing the sample is fully broken up during the blast over timescales much longer than of interest.

High Speed Video

Figure 6 and Figure 7 show stills from the high speed video taken during the tests. Along with images from this work, images from historic work of Clarke et al. [15] are included. Figure 6 shows images taken 150µs after the detonation (taken as the frame before a flash/movement is observed in the video). The stills show that the tests with a frozen medium above the charge (rows 3, 4 & 5) typically have faster moving material than those with loose sand above the charge (top two rows). Figure 7 shows stills from the high speed video highlighting the shape of the ejecta prior to impact on the target plate. These stills are at different times and were selected as the frames close to impact with the highest resolution/contrast (e.g. some are a frame earlier than impact while others are 2-3 frames before to avoid a contrast clash with a black stripe of the backdrop). These stills show that ejecta breakup of frozen sand is less uniform than that of loose sand. This is indicative of the material breaking up non-uniformly with the ejecta shape more closely resembling the breakup of 'Stanag soil' (row 5), which is a NATO standardized soil for blast testing, rather than uniform LB. In contrast, the shape of the breakup of the ice more closely resembles that of LB sand rather than water, indicating it is broken into particulate matter rather than acting as a fluid.

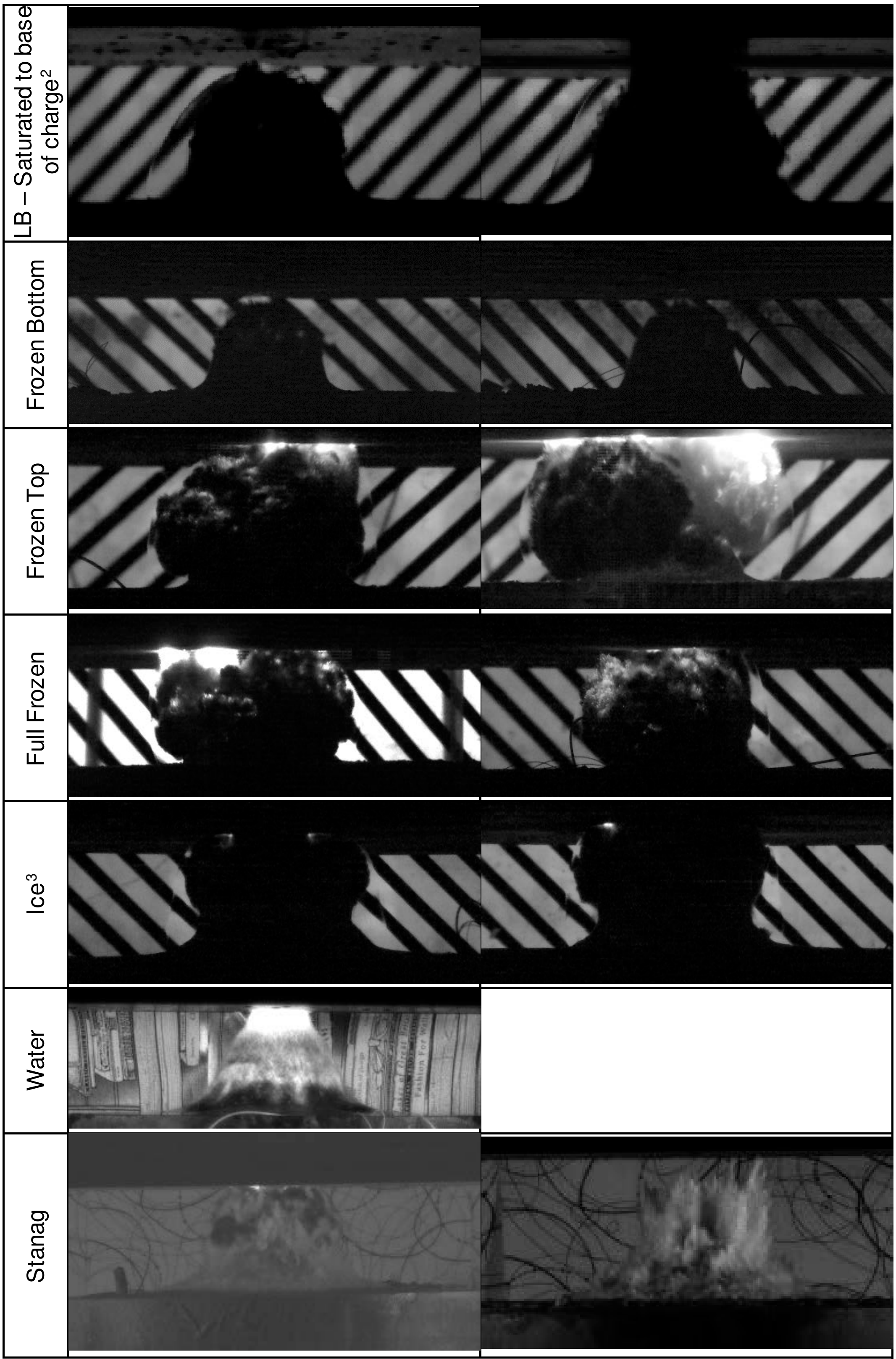

Figure 6. Stills from the high speed video showing the shape of the ejecta approx. 150µs after detonation showing how the different soil types have different breakout times

[2] Used as a baseline for dry sand breakup

[3] In one of the ice shots the fireball broke through overexposing the image, what is shown above is the fireball rather than the ejecta cloud

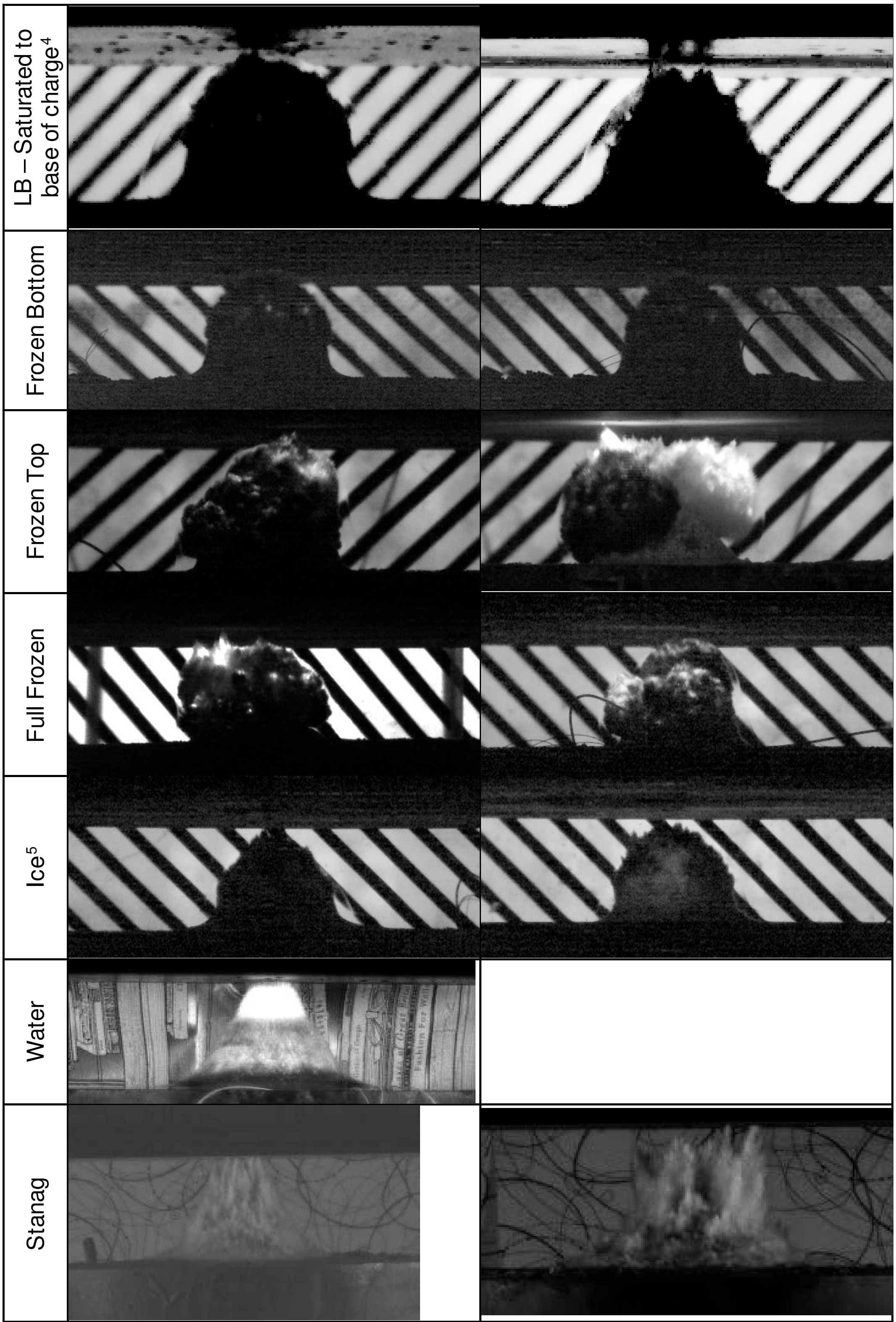

Figure 7. Stills from the high speed video showing the shape of the ejecta approximately 50mm before contact with the target plate

[4] Used as a baseline for dry sand breakup

[5] In one of the ice shots the fireball broke through overexposing the image, what is shown above is the fireball rather than the ejecta cloud

Comparison to previous results

For each shot the pressure and cumulative specific impulse of each bar is calculated and plotted. The full set of plots, and details on how the specific impulse and total impulse are calculated is included in Lodge [16].

To allow comparison to previous results, the same analysis process used for this work has been applied to three datasets from Clarke et al. [15]. Those of water, LB at 5% moisture content and Stanag soil were used. The results of these comparisons are below for specific impulse (Figure 8 and Figure 9) and total impulse (Figure 10).

Pressure and specific impulse

The specific impulse distribution for each series of data are plotted below for comparison in Figure 8 and Figure 9. On these plots, the central line is the average of all relevant data points in the given series (e.g. all bars in all tests) and the shaded area shows the standard error on the mean. Discussion of the results is included below with reference to historic data.

Specific impulse

Comparisons between the ice, water and LB sand in Figure 8 show that the ice has a lower loading than the water. The large apparent variability in the ice data at 0 mm radius is partially to the low number of data points (three compared to 12 for the other distances), as the data is plotted as the standard error of the mean, which is the standard deviation divided by the square root of the sample size. The associated variability may also be due to some as yet unexplained feature driving loading variations directly above the charge centre. The peak pressure reading for the central bar in these three tests were 250 MPa, 500 MPa and 40 MPa.

Figure 9 plots the specific impulse for the three frozen sand series alongside historic data for LB and Stanag soils. The plot shows that the frozen sand is more variable than the LB with a variability similar to Stanag.

Total impulse

The total impulse for each shot is summarised in Figure 10. The results for Shot 23 are low compared to the other fully frozen tests, however the data for this shot included a large zero offset on all channels resulting in a large degree of uncertainty on the results.

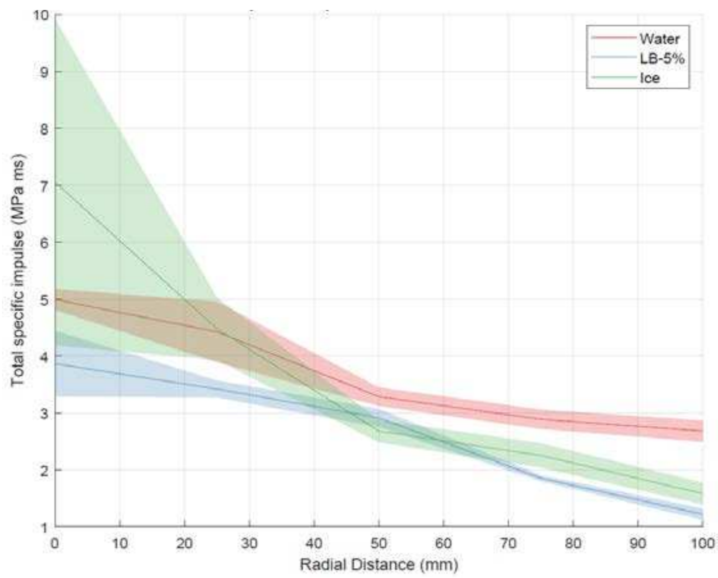

Figure 8. Comparison of the total specific impulse for the Ice series with previous data for LB and water.

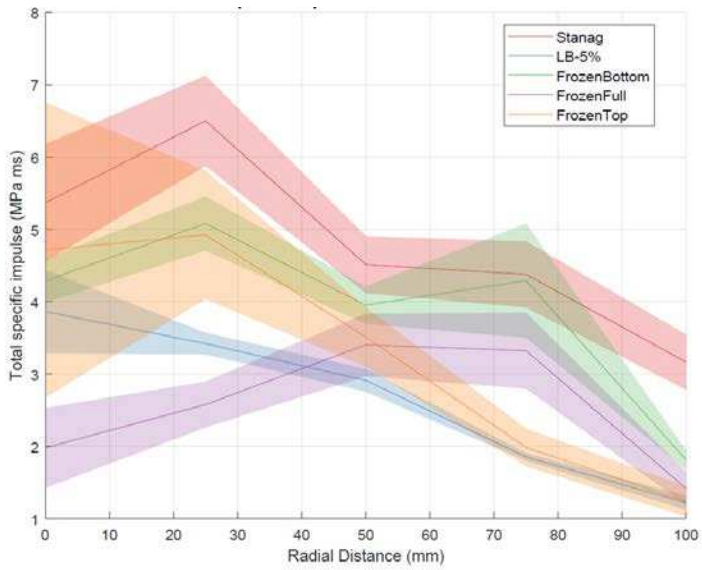

Figure 9. Comparison of the total specific impulse for the frozen sand series' along with previous data for LB and Stanag**.**

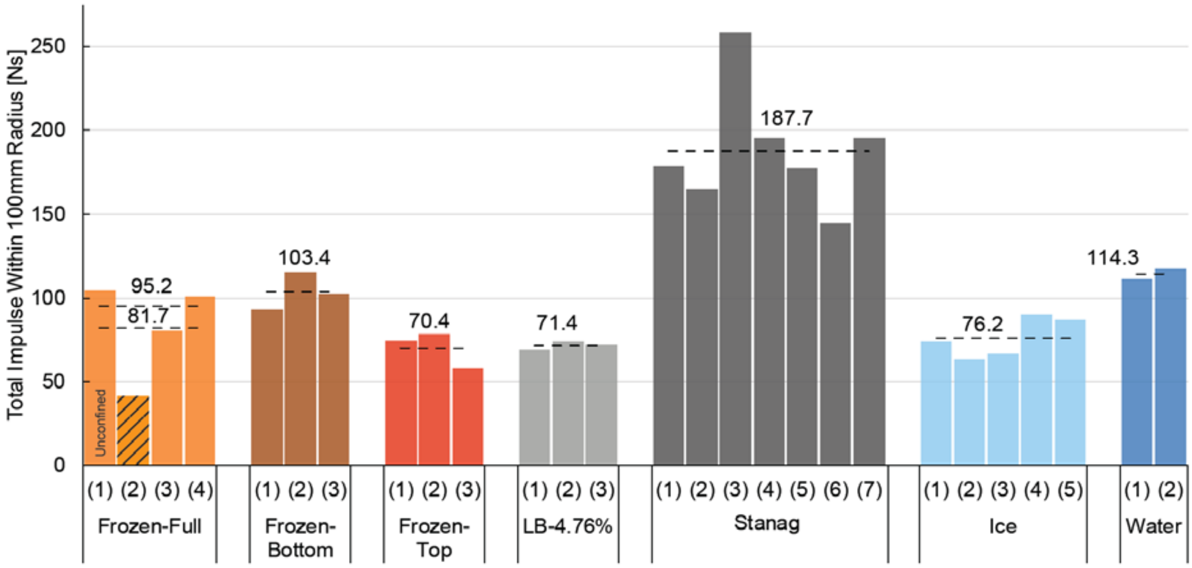

Figure 10. Chart showing the total impulse over the 100mm instrumented area, including historic data for comparison with the average for each series overlaid as a dashed line. For the frozen full series, the average has been plotted both including (81.7 Ns) and excluding (95.2 Ns) the anomalous result found in test 2.

Conclusion / Summary / Recommendations

Techniques for preparation and testing of charges buried in frozen material have been developed and implemented. The results show that testing on charges buried in frozen soils and ice have a loading profile that is significantly more variable than equivalent testing of unfrozen samples. Results have also shown that ice does not form clumps when exposed to explosive events on the scales examined, instead responding as a granular material unlike equivalent tests in water. The results for frozen sand are less conclusive, with the images showing a breakup more akin to the Stanag soil, but a loading closer to that of unfrozen LB soil.

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