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MEASURING THE SPATIAL AND TEMPORAL PRESSURE VARIATION FROM BURIED CHARGES

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Abstract

The effect of changing geotechnical parameters on the impulse generated from a shallow buried charge has been the topic of a large amount of scientific interest in recent years. Many previous researchers have utilised a free flying mass experimental approach to capture the impulse imparted from such an event. This methodology has also been used for a parametric study conducted at the University of Sheffield Blast and Impact laboratory

A new approach which aims to better capture the loading from shallow buried charges uses a fixed plate with data recorded via load transducers and spatially and temporally resolved via an array of Hopkinson pressure bars. This paper outlines the revised experimental approach for the capture of spatially and temporally resolved impulse data at the blast-target interface. Issues encountered during the commissioning tests using charges buried in silica sand are discussed, and initial results from the original and revised Hopkinson pressure bar arrays are presented.

Keywords: Buried charges; Spatial & temporal variation; Soil; IEDs; Impulse measurement.

1. Background

The effect of buried charges on structures is well documented. The influence of sub-surface blast effects has been experimentally researched [1-7] with many researchers focusing on localised structural response as a primary metric, then further developing techniques to capture impulse by various means. Many of these studies fail to draw clear conclusions by either failing to record, or to control the geotechnical conditions.

The Free Acceleration Approach (FAA) uses a freely moving ballast mass suspended above a soil bed and buried charge. The response of the mass is observed using High Speed Video (HSV) and displacement-time data is used to derive the impulse. Clarke et al. [8] used the used FAA to demonstrate that, by carefully controlling soil preparation, it is possible to achieve a high level of consistency between tests.

A second study conducted by Clarke et al. [9] investigated the relationship between Particle Size Distribution (PSD) and water content. This work attempted to outline the difference between the direct effect of mass confinement and the relationship between soil, air and water (by reducing the local volume of voids). The geotechnical parameters were kept constant between studies with exception to changing the soil particle size distribution. This work has shown that for a well graded material, the impulse variations are larger for nominally identical tests than for the same tests conducted with uniform soils.

2. Introduction

FAA has been successful at producing a principle parameter study for the geotechnical variations, but does not characterise load at the blast-target interface where localised effects may dominate the structural response. This interaction is key to developing an understanding of how load is applied to the target and may provide further information of the soil bed material constitutive behaviour. In this study the development of a new trials apparatus which aims to characterise blast loading will be discussed. The component parts of the test rig are; an effectively stiff reaction frame constructed from fibre and steel reinforced concrete, into which a 50 mm thick acceptor plate is cast. Load transducers are fixed between the underside of the acceptor plate and a 100 mm thick target plate which has an arrangement of holes that accept 10 mm diameter Hopkinson Pressure Bars (HPBs). On the top face of the concrete beam, a HPB support frame is bolted and aligned so that the bars are suspended vertically above the soil bin.

This paper will outline that strict geotechnical control, working at acceptable scales and developing instrumentation that is robust enough to survive loading potentially in the GPa range but sensitive enough to capture 1MPa and below will generate consistent pressure-time histories at discrete points for buried charges.

3. Trial methodology

The impulse from a detonated buried charge can be measured in various ways. The choice of method depends to some extent on the magnitude, rate and duration of impulse and, whether spatial-temporal resolution is desired. Whilst by no means exhaustive, two possible methods are discussed below. The FAA methodology allows a mass to translate freely, and by accurately measuring its displacement the global impulse can be derived. Alternatively, by preventing the target mass from translation using an effectively stiff reaction frame, load-time history can be recorded, here termed the Fixed Plate Approach (FPA). A further refinement of the FPA is to measure pressure at points in the target plate providing spatial-temporal resolution.

The advantage of the FAA is that it can simulate the vertical movement of a suitably ballasted structure. This vertical movement is likely to lessen the effect of long term loading by increasing the stand-off between the structure and detonated products. Conversely the FPA creates an artificially fixed boundary which is likely to overestimate loading. Clearly the FAA is not compatible with load transducers and there are further limiting engineering implications for instrumentation deployment. Consequently, the key advantage of the FPA is flexibility to deploy a range of instrumentation schemes.

3.1. Expected loading features

Work conducted by Taylor et al. [10] and Tyas [11] has used HPBs to measure the load on a plane above the soil surface following the detonation of a shallow-buried charge. In both works an effectively rigid plate was placed above and parallel to the soil bed surface. Whilst the scaling used in these test differed by an order of magnitude, they confirm the presence of several key features illustrated in the indicative pressure time history in Figure 1. Including: (a) an initial pre-cursor load; (b) a very high magnitude, short duration “shock” pressure; (c) a post-peak plateau with a rapid fall off to low magnitude and then (d) a long duration very low magnitude pressure.

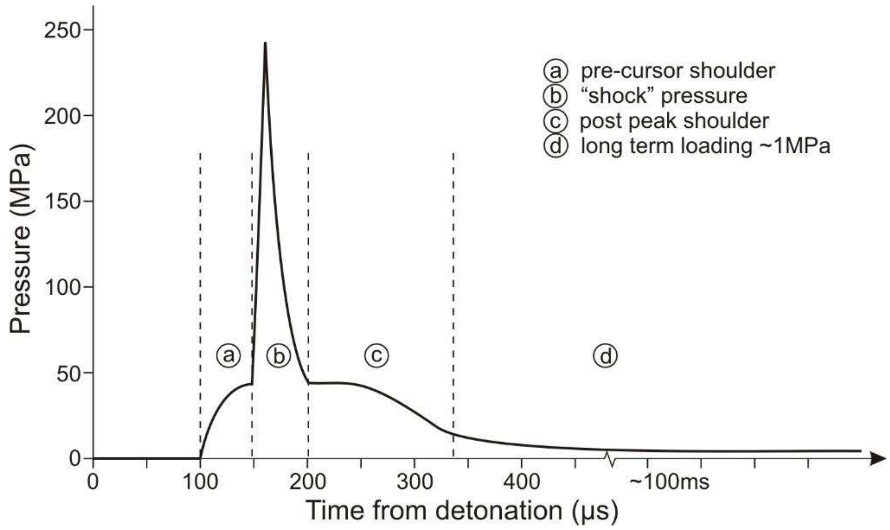

Figure 1: Indicative pressure time history (NB - durations dependant on scale)

Analysis of the work published by Taylor et al. [10] indicates that the loading following 100μs is of very low magnitude but long in duration – area (d) in Figure 1. Whilst this is perhaps important for the analysis of rigid-body response, it is unlikely to contribute significantly to the localised behaviours of a target. This is critical as it allows instrumentation to be robust and therefore relatively insensitive in order to concentrate on the high-magnitude, short duration load. Numerical analyses have been run to confirm that this is the case. The worst case numerical analysis being one where the impulse in area (d) is three times that in areas (a)-(c), this resulted in a 12% increase in the overall peak displacement of a deformable plate, when compared with no impulse in area (d). Full details of this can be found in Clarke at al. [12]. In the current work HPBs were also chosen as the instrumentation scheme of choice.

3.2. Geotechnical control, soil selection and scaling.

Control over the geotechnical conditions are a key factor in generating well characterised load curves. Many variables contribute to the impulse applied to a target including; dry and bulk density, moisture content, particle size distribution, explosive burial depth and stand off as well as explosive type. Small variations in the geotechnical condition for nominally identical tests can lead to disproportionately large variation in test results. Furthermore, it is important in preliminary tests that the soil itself has little natural variation such that spatial variation of load is not a by-product of soil type.

Geotechnical preparation followed the same standards set by Clarke et al. [8, 9] where conditions in the soil bed were achieved by pre-mixing the soil and water to the required quantities then compacting the mix at a predefined volume. Due to its uniform nature, a single fraction (0.6-1.18 mm) of Leighton Buzzard (LB) sand was used. The variation of the natural density of this soil is very low, so the filling process is simplified somewhat by the sand’s ability to pack itself.

It was also required that the experiment should be conducted at as small a scale as possible whilst allowing a controllable burial depth when using sub-surface charges. The NATO standard for buried charge testing specifies a burial depth of 100 mm in full scale tests. With very shallow depths <20 mm, the soil overburden would be very difficult to control. To allow for extremely tight control over the soil bed and to facilitate indoor testing, 1/4 scale tests are used. This lowers the amount of soil required in each while giving a controllable burial depth (25 mm). At 1/4 scale the charge size required to scale down a full scale 5 kg charge is 78 g.

3.3. Test arrangement

A schematic of the test setup is presented in Figure 2 below. It should be noted that a flexible approach to the positioning of the HPBs has been adopted allowing bars in a radial (along a given axis) or circumferential (a constant radius along 4 axes) arrangement.

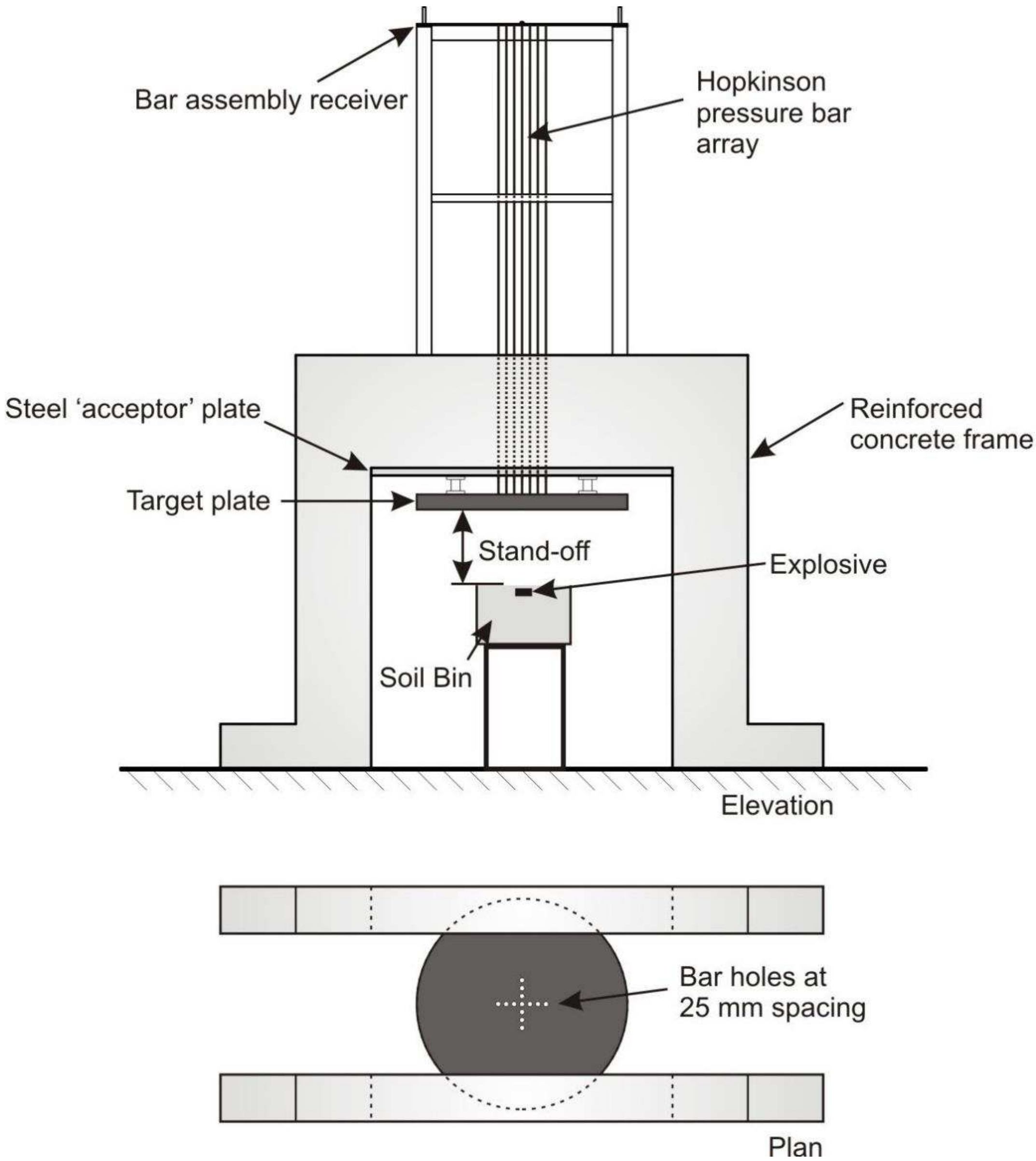

Figure 2: Test frame schematic – not to scale

3.4. Geotechnical preparation

Soil bins are constructed from 30 mm thick rolled steel plate formed into 500 mm diameter cylinders 375 mm in height (Fig.3d). A 25 mm thick base plate is welded to the cylinder, to which, four lifting eyes are welded. Before soil bins are filled, test debris is cleared from the bin and the bin is then checked for dimensional changes that may have been caused by the previous test. The moisture content of each bulk bag is checked so that the prescribed water content may be calculated, as the moisture content will dictate the amount of sand and water weighed into the forced action mixer.

Prior to filling the soil bin is levelled to ensure even compaction and cleared of previous test debris. Soil is weighed as it enters a forced action mixer. When the mixer is at the correct mass water is added, the weight of the mixer is checked and the mixer activated. Mixing continues until water appears evenly distributed at which point a 0.1 kg sample is checked for its moisture content. If the moisture content of the sample is within ±0.1% of the prescribe moisture content, the mass and moisture of the mixer's contents are recorded and the first lift may begin.

Lift 1: 60 kg of soil is purged into the soil bin and the surface is levelled. A timber board (Fig.3a) is placed on the soil surface and the height recorded and checked against expected results. A stiffened steel compaction tool (Fig.3b) is placed on top of the timber board and mechanically struck until the required density is achieved. Measurements of the soil height are checked and recorded, if the soil layer is in tolerance, the stiffened steel compaction tool and timber board are removed in preparation for the second lift.

(a) (b) (c) (d) (e)

Figure 3: Images of soil preparation equipment: (a) timber ply board (b) stiffened steel compaction tool (c) steel collar (d) soil bin (e) soil bin filled with LB being marked for charge placement

Lift 2: The final lift makes up the surface of the geotechnical bed. The compaction and filling technique are identical to lift 1. However the un-compacted soil will exceed the volume of the bin. A laterally restrained 150 mm deep, 500 mm internal diameter steel collar is seated on the lip of the bin (Fig.3c). 60 kg of soil is placed in the bin and levelled, the soil height is measured and checked against previous results. A timber board and steel compaction tool are placed on the soil surface, the steel compaction tool is mechanically struck until the soil surface reaches the soil bin lip. The steel compaction tool and timber boards are removed from the soil bin. A small amount of soil should be protruding from the soil bin - <1 kg. The protruding soil is tamped into the soil bed with a steel screeding tool. When the soil bin is complete the exposed surface is sealed with plastic sheeting and transported to the charge preparation area.

3.5. Data capture and analysis technique

Strain gauges on the HPBs produced voltage time histories which were recorded by TiePie HS4 at 14-bit 1.35MHz 50k samples in csv format. The csv files were then imported into an analytical software package and post processed. Zero shift was removed by subtracting an average of the data points up to the arrival of the first shock. Noise was reduced, as required, by either taking a running average or using a low pass filter.

Voltages were converted to stresses using the gauge factor (GF) of the strain gauges, elastic modulus of the bar (E) and powering voltage (V0) using the following equation:

$$\text{Pressure} = (2*E)/(V0*GF) \qquad (1)$$

Impulse was calculated through numerical integration of the pressure time curve. Pressures and impulse for all bars, and their corresponding time axis were then saved as a data file entitled with the shot number allowing ease of plotting and comparison between shots.

3.6. Test conditions

All PE4 charges were cylindrically shaped with an aspect ratio of 3:1 and were contained within 3 mm thick PVC cases. 25 mm overburden was measured to the top of the charge case. Where the 3 mm case top has been removed, the charge overburden is 28 mm i.e. maintaining the same burial depth. All geotechnical preparation was using LB sand at 2.45% moisture content and 1.635 bulk density. The stand-off (measured from the geotechnical bed surface to the strike face of the target) was 69 mm.

4. Results and discussion

Free air tests were conducted to check consistency against ConWep, these tests were found to give a very high level of confidence in the ability of the experimental setup to capture the loading [12]. The main aim of this paper is however to discuss the exact issues surrounding the preparation of the charge and the recording of the loading from buried charges, with the test details given below in Table 1.

Table 1: Test details

Test Identifier	Bar Array	Detonation type
A	Circumferential (r = 100 mm)	Top (Davey)
B-D	Circumferential (r = 100 mm)	Bottom (Non-el)
E	Circumferential (r = 100 mm)	Bottom (Non-el, no cap)
F	Radial	Bottom (Non-el, no cap)

When commissioning the experimental setup for use with shallow buried charges, initial tests were conducted where the charge was detonated from the top such that the detonator and cable umbilical protruded from the soil surface. The cable umbilical consists of a command line used to detonate the charge and a break wire. Artefacts seen in the pressure time histories of test A (Fig. 4) were possibly caused by detonator fragments striking the HPB loading face and electrical noise from the break-wire striking the attack face of the target plate. Poor test-to-test consistency in the pressure data was believed to have been caused by the detonator casing and the cable umbilical striking the loaded face of the HPBs intermittently. Figure 4 does however still show the main features illustrated in Figure 1.

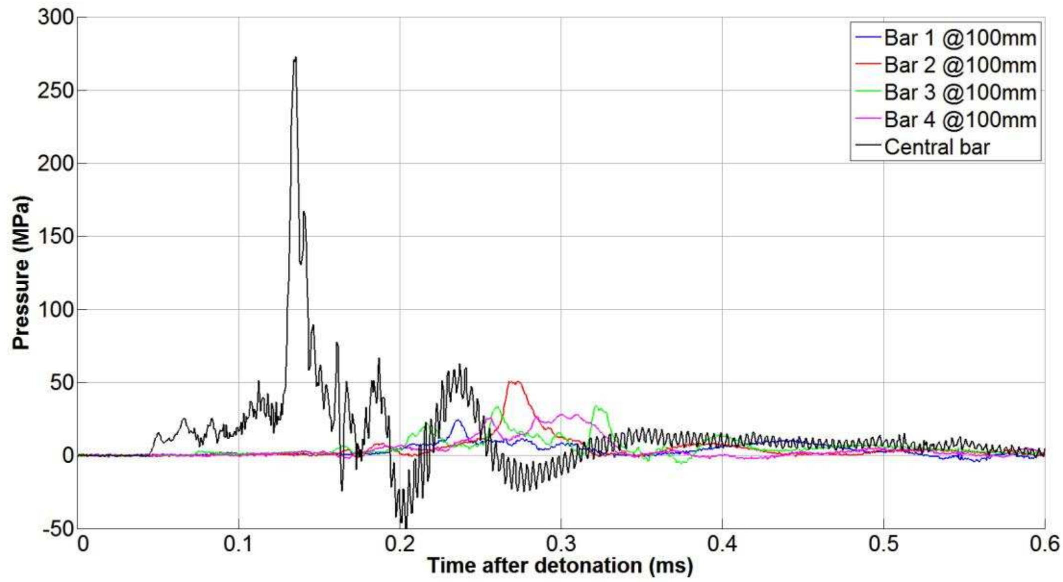

Figure 4. Test A, pressure-time history, top detonation

As the signal generated by the commissioning shots appeared to contain anomalies caused by the method of initiation and triggering, further commissioning shots were conducted with the cable umbilical and detonator (Fig. 5a) placed at the base of the charge, with a channel burying the cable umbilical from the soil bin centre to the side wall (Fig. 5b).

(a) (b)

Figure 5. Images taken from charge preparation process: (a) non-el detonator and break-wire umbilical prepared for burial (b) charge hole and umbilical trench prepared

The results of test B are shown in Figure 6 and by comparison with Figure 5, the pressure-time histories appear free from detonator fragment impact and electrical noise. Excellent test-to-test consistency can be seen when comparing the central bar traces in tests B-D (Figure 7) which confirms that the explosive engineering issues were largely resolved.

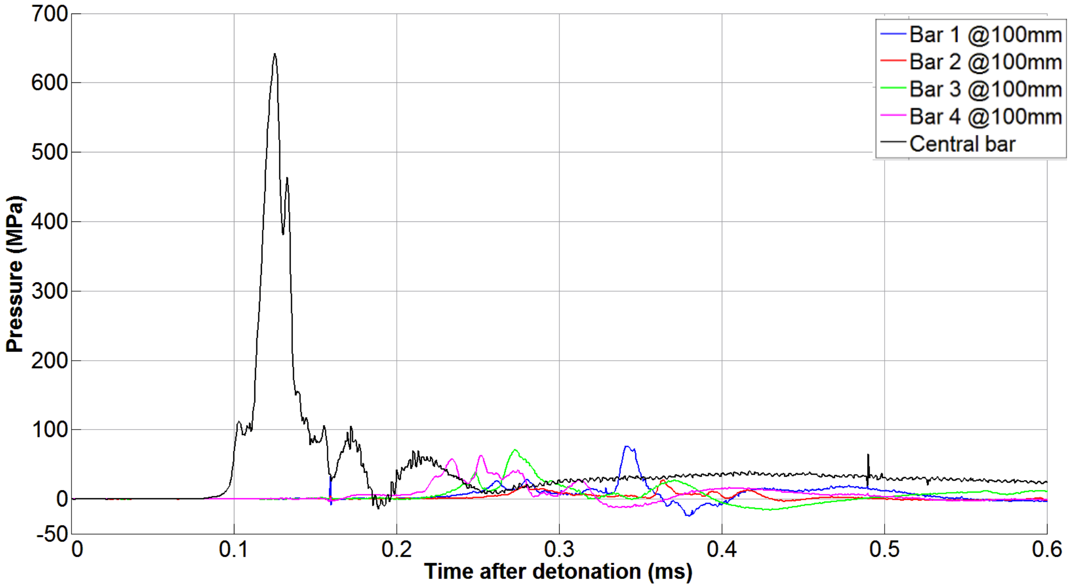

Figure 6. Test B, pressure-time history, base detonation

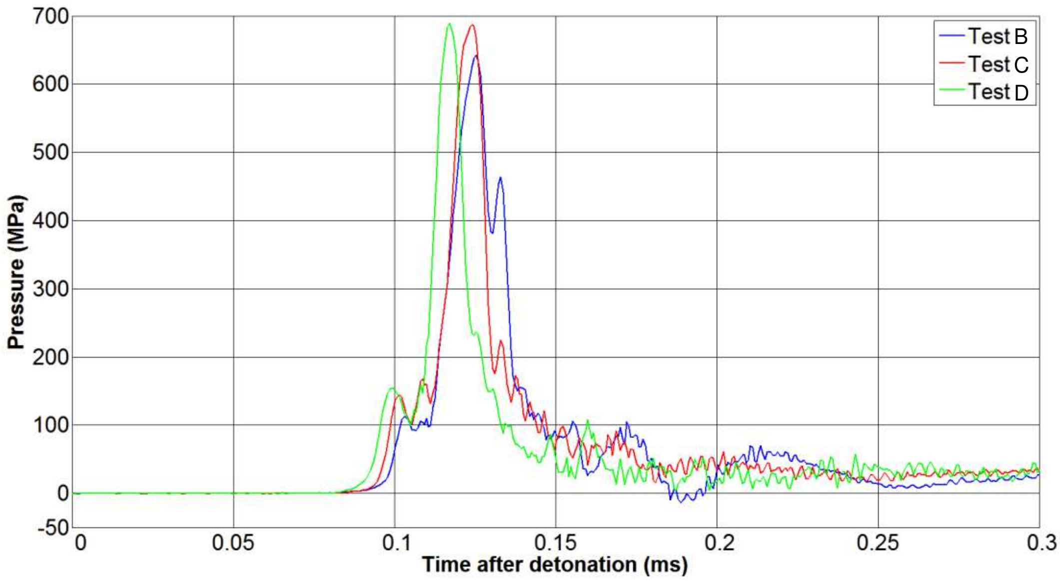

Figure 7. Tests B, C and D, pressure-time histories of central bar, base detonation

It was noted that during the testing there was another possible source of debris that could interfere with the results – that of the charge casing. The lateral casing was thought to play a minor role but the cap of the charge case could introduce spurious features in the recorded traces. In test E, the exact same conditions were used but the charge casing cap was removed. As was mentioned earlier, in this test the burial depth was increased by the thickness of the cap to give the same distance between the charge surface and the soil surface. It can be seen in Figure 8, that while the trace for the central bar looks very similar to those in Figure 7, there is one area where there is a distinct difference – the pre-cursor shoulder. In test E this effect is much reduced so it can be argued that the appearance of this feature in previous work [10, 11] could simply be down to the explosive casing.

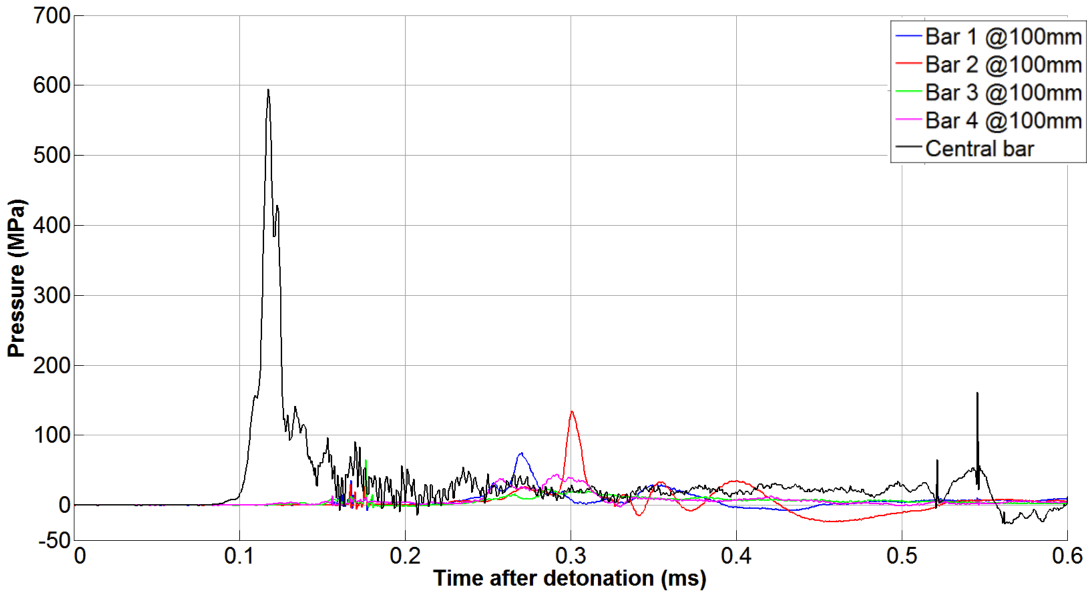

Figure 8: Test E, pressure-time history, base detonation, no casing cap

With the current research focussing on the accurate quantification of the loading, it was decided to base initiate all future tests and to use uncapped charges.

Unlike the central bar which showed very repeatable results, the pressure-time histories of the 100 mm circumferential bars differed in magnitude and arrival time in all tests, which can be seen in both Figures 4, 6 and 8.

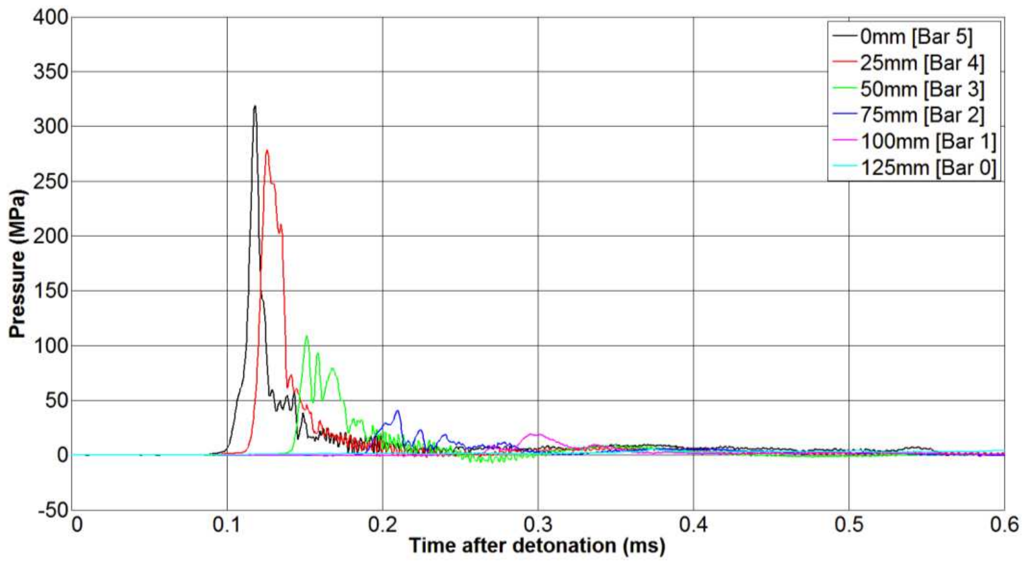

Figure 9: Test F, pressure-time history for a single radial array of 6 HPBs from 0-125 mm

Further testing was conducted with a single radial array of bars spaced between 0 and 125 mm at 25 mm spacing along a single axis to develop a better understanding of the spatial variance. The results of test F are shown in Figure 9.

The central and 25 mm HPBs fall within the radius of the charge diameter and pressure at these locations is typically similar in magnitude and arrival time. Pressure measurements beyond 25 mm rapidly drop off – the peak pressure of the bar at 50 mm is typically 30% of the central bar with a progressive fall off thereafter. Again the very much reduced pre-cursor shoulder can be seen, with no shoulder at all appearing in the 25 mm bar.

Figure 10 shows and indicative peak pressure-run out distance. As may be expected, the majority of the pressure develops above and around the periphery of the charge. This rapid drop-off in pressure could be at any point between the between 25 and 50 mm illustrated by the green, red and purple curves in Figure 10. The gradient of this drop-off may be important when assessing the behaviour of deformable targets.

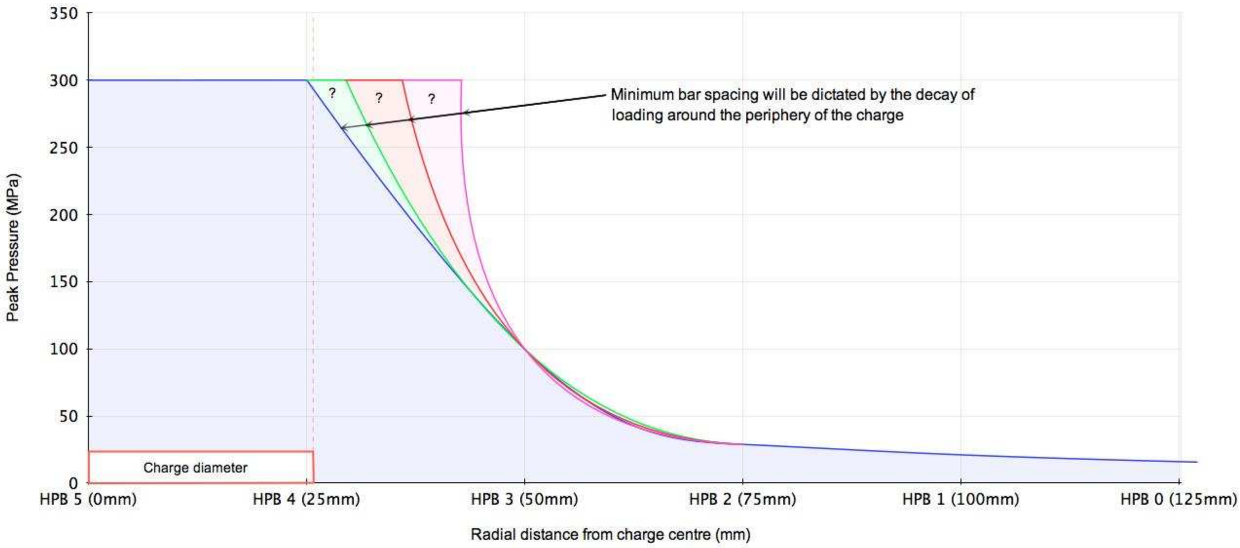

Figure 10: Indicative peak pressure versus run out distance from charge centre

CONCLUSIONS

The experimental methodology presented has been shown to be able to capture the spatial and temporal loading from a buried charge. The resulting test data clearly shows that the original top detonation charge configuration gave erroneous results. Whilst this may not have affected the total impulse that the target plate witnessed it has caused anomalies in the data, namely a much longer duration pre-cursor shoulder and electrical noise in the general signal. When the charge configuration was changed to base detonation, data was much more consistent test-to-test and without the presence of features believed to be have been caused by detonator fragments and the cable umbilical. This effect was further refined with the removal of the charge cap which greatly reduced a feature that had been seen in previous work.

Variance of pressure outside the geometry of the charge is a consistent feature of the testing to date. This implies that there is some inherent variance in the pressure distribution across the target face, which is likely due to very small rotations in the charge giving a focus in one direction. For all tests conducted a clear pattern has been observed in peak pressures – fairly consistent between 0 and 25 mm then a rapid drop-off to 50 mm and a progressive fall off beyond that, at least in the case of the low moisture content tests presented.

To improve upon the current understanding of the pressure distribution across the target face, it is clear that that HPB should be deployed across more than a single axis and a close centres so that any out of alignment between the charge and the target plate can be assessed.

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