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Characterisation of Underwater Shock Parameters in Shallow and Open Water Conditions

Dain Farrimond[1,2], Piotr Nowak[3], Lewis Tetlow[1,2], Tommy Lodge[1,2], Genevieve Langdon[1], Andy Tyas[1,2], Piotr Sielicki[3], Tomasz Gajewski[3], Elliot Tam[4], Mark Whittaker[4]

School of Mechanical, Aerospace and Civil Engineering, University of Sheffield, S1 3JD, UK

1 University of Sheffield, Sheffield, UK

2 Blastech Ltd, Buxton, UK

3 Poznan University of Technology, Poznan, Poland

4 Defence Science and Technology Laboratory, Salisbury, UK

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Abstract

Understanding pressure propagation in shallow seas has a major impact on ensuring safety during coastal munitions clearance. Simple mathematical formulas are used to determine the 2D hazard area when considering underwater shock, cavitation, and bubble parameters in open water. However, the influence of the explosion depth can make a significant difference to the loading in shallow water conditions. A series of small-scale underwater explosive tests were undertaken to investigate the behaviour of underwater shock waves, focusing on shallow and open water conditions. Test-to-test consistency and repeatability were considered when focussing on key blast parameters of pressure, impulse and arrival time. A bespoke manufactured frame was designed to connect the explosive charge to a sensor array for accurate distance and depth measurements, the results of which are compared to open water recordings both recorded within this test series and extracted from published literature. These comparisons show excellent agreement and shot-to-shot consistency with empirical prediction tools presented.

Introduction

Characterising and quantifying the behaviour of explosive events within air, and how the propagating fireball and shock wave interact with structures has been at the forefront of most blast research, with semi-empirical prediction methods developed for simplistic blast-obstacle interaction scenarios [1]. Within water as a medium there are significant differences in the shock wave propagation characteristics due to fundamentally different physical properties. When detonation occurs in water, the sudden energy release results in a conventional shock wave and a highly compressed gas bubble within the water [2]. The expansion of explosive gas products into the surrounding medium, and the subsequent interaction with medium interfaces between the meadium and expanding gasses, both undergo wave phenomena contrasting to those in air [3]. Prediction methods of these behaviours have yet to be established or fully investigated [4].

Structures in marine environments can be exposed to blast loads generated both above the water surface in air, and within the water medium itself and therefore it is important to characterise the shock behaviours in both media and also the interface effects. There are a variety of published articles which consider the loading and response of materials that are exposed to submerged blasts. Several authors investigated the response of plates exposed to submerged blasts and examined the loading profiles and cavitation phenomena [5-9]. Few are published which detail the generalised behaviour and characteristics of free-water and shallow water blast wave parameters. Liang et al [10] suggested that the majority of structural damage in marine environments from submerged blast events is a direct result of primary shock interaction and therefore characterising these behaviours within shallow water conditions is critical. Consistency of small-scale explosive air-blast trials has been investigated and shown to align with large scale results when scaled accordingly [11]. Gramme-scale trials have therefore been utilised within this article to capture underwater explosive shock parameters to remove associated experimental risks and improve measurement accuracy.

This paper presents the results from 39 experimental trials conducted with the UNDEX facility located at the University of Sheffield which aimed to assess the influence of strata and water depth on recorded blast parameters. To do so, the UNDEX tank was filled to a designated height with Leighton Buzzard (LB) sand, a well characterised soil type when considering the consistency in results from blast related trials when strict control measures were implemented [12] and topped off with clean fresh water. Within each trial, a 5-20g sphere of PE10 explosive (86% PETN, 14% binder-plasticizer), with a TNTe=1.22 [13], was placed at various depths within the water medium. This was centrally detonated using a Euronel non-electrical detonator (0.8 g TNT equivalent mass of explosive) with two varieties of pressure gauges located at recorded locations within the tank to spatially map the variation in common blast parameters.

This work makes direct comparisons between the gauge types used, presenting key similarities and differences. Further comparisons are also made between two methods of explosive and pressure gauge placement which consider the consequences of using a structural mount for precise standoff measurements when comparing to free-field mounting which is subject to movement within the water but minimal shock-structure interaction. The overall findings of this provide predictive methods for generalised blast waves from submerged blasts, considering shot-to-shot consistency and proximity to interfaces.

Experimental Work

The UNDEX facility, shown schematically in Figure 1, was used to perform 39 trials, which consisted of 341 individual pressure-time history recordings. Explosive testing was undertaken within a 2m diameter cylindrical open-topped tank with an internal height of 2m fitted with portholes for optical high speed video recordings. Sufficient clarity of water (to capture HSV footage) was achieved using the overflowing action of a receptacle during pumping.

A combination of PCB 138A10 underwater blast transducers and Neptune T11 shock gauge transducers were utilised to compare recorded measurements from two different gauge providers and construction type. A Line-powered ICP sensor signal conditioner Model 482C05 and Kistler LabAmp Type 5165A4 were utilised respectively to power the aforementioned pressure gauges with no additional pre-filtering applied to any of the signals. The gauges were placed within the water such that the scaled distance ranged between 1.0–6.5 m/kg$^{1/3}$ from the explosive itself, with the depth of the explosive mass and gauge within the water also recorded.Recordings were triggered off a breakwire signal (the breakwire itself was wrapped around the detonator) using a 16-bit digital oscilloscope and TiePie software, with an average sampling rate of 131k samples at a rate of 1MHz.

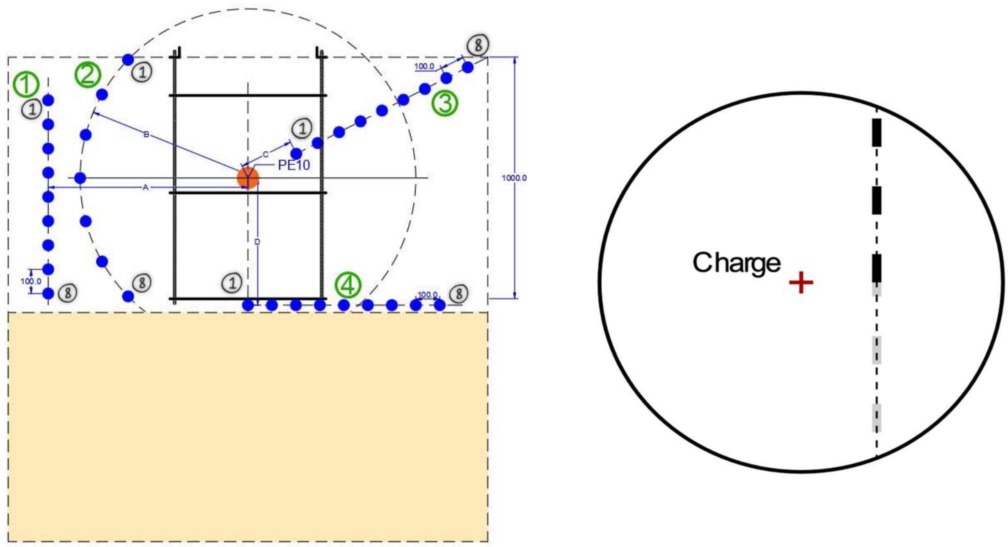

Figure 1. Schematical drawings showing mounting type 1 (left), the structural method with green numbering denoting the gauge position layouts, and mounting type 2 (right) which presents a plan view of the pressure gauges on thin cables affixed to tank walls.

The two methods of explosive and gauge placement are utilised to compare the behavioural differences of shock recordings with time between that which is influenced by an imposing structural system with precision in charge and gauge locations– ***Mounting Type 1*** (schematically shown by Figure 1 (*left*) and photographed in Figure 2) and minimal influencing with less placement control system – ***Mounting Type 2*** (schematically shown by Figure 1 (*right*) and photographed in Figure 3).

Figure 2. Photographs of the Mounting Type 1 – Structural Influencing with precise charge and gauge placement with respect to one another, showing both pre-test placement and in-situ of water.

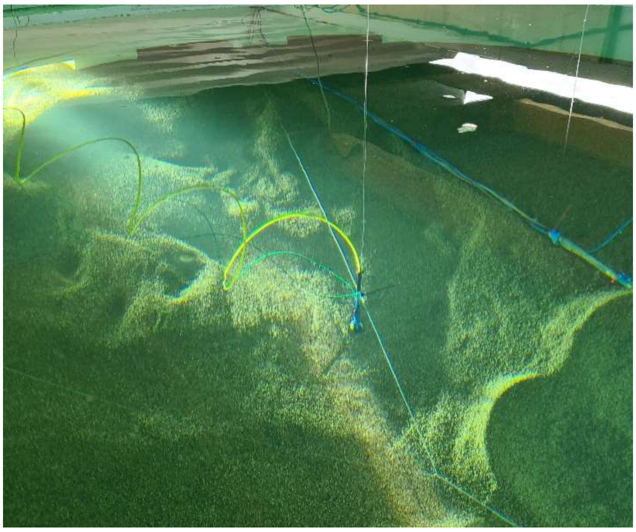

Figure 3. Photographs of the Mounting Type 2 – Minimal shock Influece with gauges and charge placed on thin wires but highly less control in placement

Consistency in the Data

To assess the influence of mounting type on shock wave behaviour and recorded pressure-time histories, Figures 4a and 4b below compare a 5g PE10 sphere detonated centrally of the tank, at a depth of 0.5m below the water level (1m total) with recordings taken at a standoff distance of 0.745m from the charge, also at a depth of 0.5m below water level. Although the data shows significant differences in peak recorded overpressures and specific impulse, it is important to note that the data is still comparable qualitatively. The variation in these traces is attributed to reduced accuracy in the charge and gauge placement when using Mounting Type 2. In this test, both the gauge and charge were fixed with minimal constraint, with the flexible line being influenced by self-weight sagging across the 2m diameter tank, which was then influenced further when water was added. This reduced the confidence in the accuracy of these specified locations, potentially leading to variations in the test data. In contrast, Mounting Type 1 utilises a fixed steel frame to secure the charge and gauges, thereby providing greater confidence in placement accuracy.

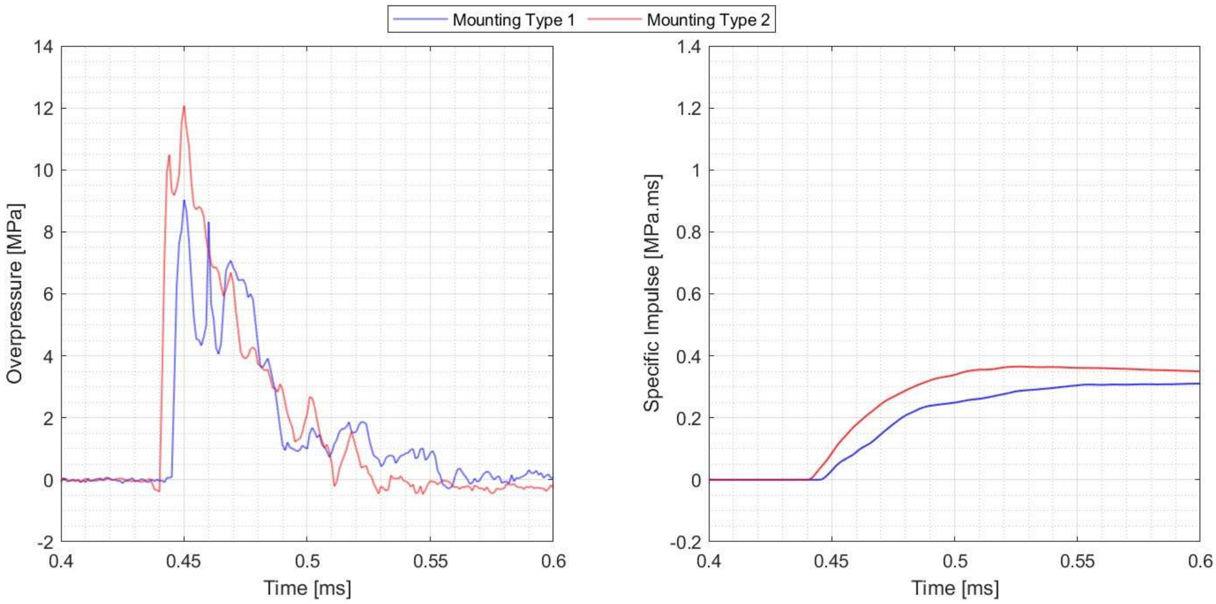

Figure 4 – a) Pressure-time and b) specific impulse-time histories comparing the effects of mounting type on nominally identical test criteria

Testing alternative gauge types allows us to evaluate the functionality of each product, which is helpful when designing future experiments to apply the most appropriate system for the given task. Figures 5a and 5b present a comparative study between the performance of a PCB 138A10 underwater blast transducer and a Neptune T11 shock gauge transducer, both mounted using Mounting Type 1, to ensure precise gauge and charge placement. It is important to note that during the trials, the charge was again located centrally of the tank, at a depth of 0.5m below the water surface (1m total), with the gauges positioned at a standoff distance of 0.461m from the charge at a depth of 0.8m below the water surface. The recordings from both gauge types were highly consistent across two nominally identical trials, with slight variations attributed to test-to-test repeatability rather than gauge performance. These analyses gave the authors confidence to proceed with a full batch analysis of the trials to assess consistency across all 39 trials.

Each pressure-time history within this series has been processed to acquire the arrival time of the shock wave and its corresponding peak overpressure. Underwater explosions are complex when considering material interfaces. Once the charge initiates, the position of the charge with respect to material interfaces influences the overall proportion and propagation of energy. At this stage of the analysis, depth as a parameter has not been considered due to the assumption that an explosive charge fully submerged in water will allow for a full energy release and shock wave propagation within the water meaning the complexity of the initial detonation can be ignored. This means that the downstream measurements of arrival time and pressure are a function of the shock propagating through water alone before interacting with a gauge, and not a hybrid of an air-water or water-soil interface. Figure 6a and 6b represent the arrival time and corresponding overpressure with respect to the scaled distance the measurement was taken away from the detonation point.

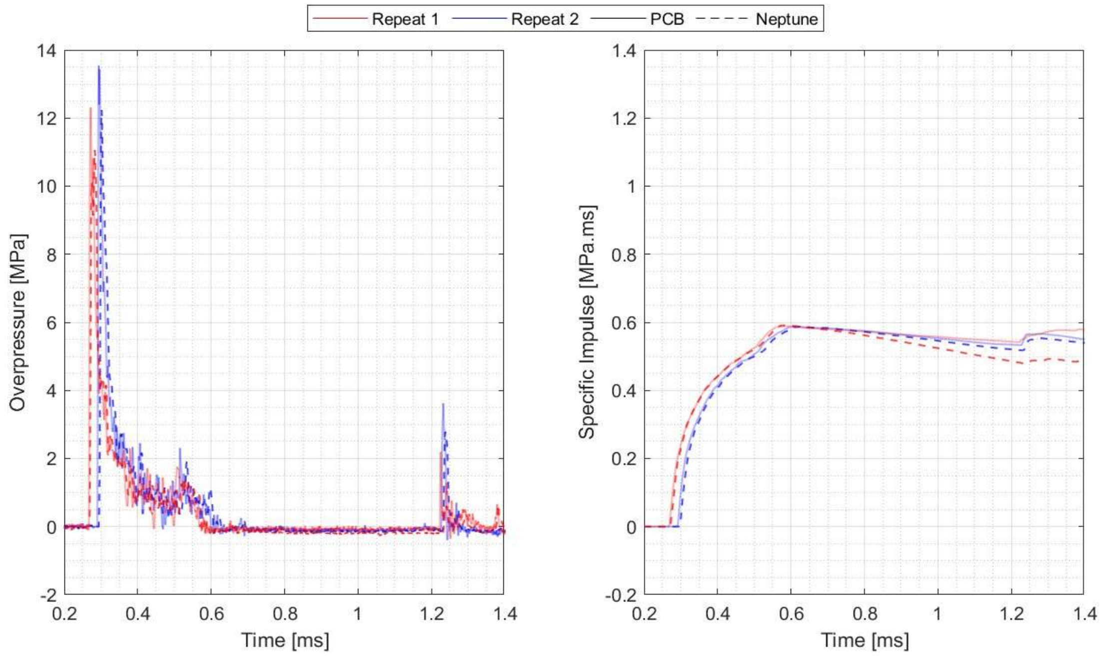

Figure 5 - a) Pressure-time and b) specific impulse-time histories comparing the effects of gauge type on nominally identical test criteria

Considering Figure 6a alone, there a clear linear correlation between arrival time at the measured distance as we increase distance, thus meaning the shock is travelling at a constant speed. Drake et al [14] considered the propagation of a shock wave through rock mediums as a result of an explosive event and found that after the initial cavity formed the shock speed was constant; this corresponded to a scaled distance of 0.155m/kg$^{1/3}$. This assumption was considered for the behaviour within water, with a linear fit forced to meet these criteria evaluated and plotted. The extracted gradient from the plot corresponds to a constant wave speed of 1477m/s, which is the approximate sound speed of fresh water. Figure 6b represents the peak overpressure for the shock wave as a result of a fully submerged explosive which is not influenced by any material interfaces until after the arrival of the shock. Quantitatively there is a clear relationship between pressure and scaled distance with an acceptable level of consistency across nominally identical trials. A curve fit as been applied to data set to establish a predictive curve for the shock overpressure for underwater charges. Future work will look to conduct trials on different scales to validate the curve fit across multiple explosive mass scales.

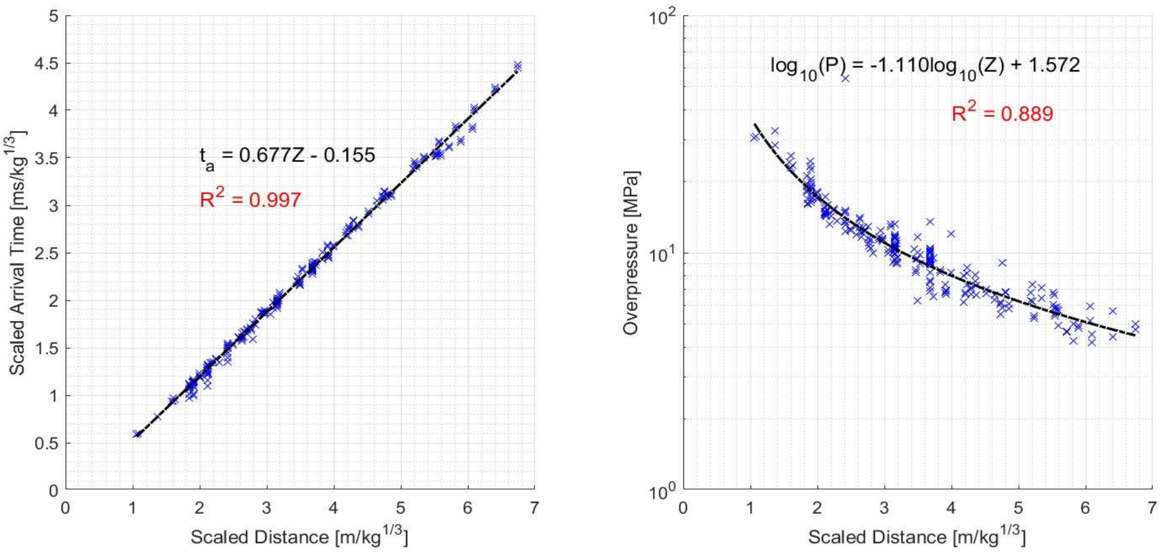

Figure 6 - a) Scaled arrival time and b) peak overpressure against scaled distance for all underwater explosive trials whereby the charge was fully submerged in the water.

Shallow Water Conditions

Once an explosive mass is detonated underwater, the shock wave will propagate outwards until an interaction with an interface occurs. These interactions can be separated into two groups: the water-air interface, and a water-material interface. Considering the former, once an underwater shock wave reaches the water-air interface, due to material impedance mismatch, an amount of the shock wave is able to transmit into the air, whilst the remaining energy is reflected back through the water medium which results in a rarefaction wave. Water is unable to retain considerable amount of tension load, therefore resulting in cavitation phenomena, where the shock pressure drops below the ambient pressure of water.

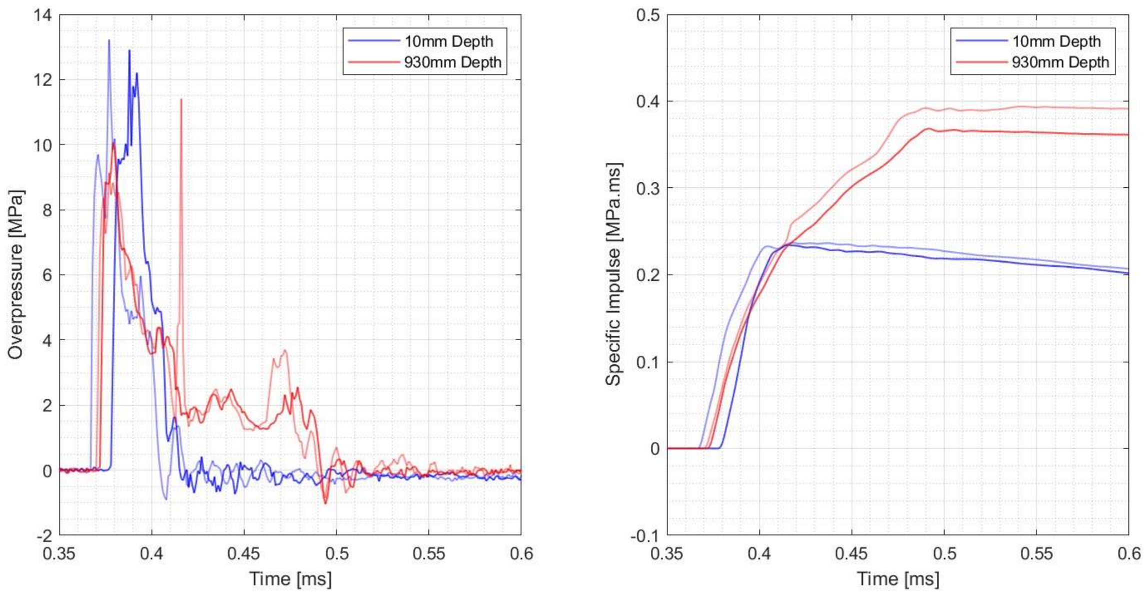

Figure 7 - a) Pressure-time and b) specific impulse-time histories comparing the effects of gauge position regarding the proximity of the gauge to the water-air interface

Figures 7a and 7b present a comparison of two gauges at the same standoff distance, 0.73m from the explosive detonation, but with the gauge located at two different depths, 10mm and 930mm within a total water body of 1m. Highlighted within these results are that the shock wave arrives as approximately the same time, the magnitudes and general form are qualitatively consistent between the two depths, but as approximately 0.415ms after the detonation, a significant and near-instantaneous reduction in pressure is recorded on the gauge at 10mm depth below the water-air interface which is not seen in the trace at 930mm depth. This aligns with the physical mechanisms of the cavitation phenomenon, with water being unable to withstand tensile forces.

Conversely, when considering a water-material interface boundary, the reflection of a shock wave could result in a compression wave propagating away from the surface and superimposing with the original shock. This behaviour is governed by the differing material properties at the interface and can be assessed by considering the specific impulse of the shock waves. Figure 8 represents the maximum specific impulse recorded for the initial positive phase of the shock wave recorded with marker colour indicating the depth at which the gauge is located within the water. Three distinct regions of loading behaviour can be identified which align with interface mechanisms. Closer to the water surface (the lighter colours), gauge recordings are shown to have loading relief when compared the overall behaviour within the domain tested, aligning with the low tensile capacity of the water at the air interface. When the gauge is located at significant distances away from any interface, therefore deemed to be free water (blue hue colours), the loading is the maximum measured in these scenarios. The variation of these data points is believed to be related to the distance a given measuring location is to tank boundaries, meaning a reflected shock could induce an increase in impulse which is accounted for in the analysis. The final region of interest is when the gauges are located towards the water-soil interface (darker colours). There are two distinct behaviours present, those that compare well to the water-air interface, and those which compare to the free-water results. The underlying behaviour behind the increased loading scenario is related again to the proximity to the tank surfaces creating compressive waves which interact with the gauge within the positive phase. The reduced loading, however, is a behaviour related directly to the saturated sand strata when loaded, which allows the sand to compress, meaning a similar behaviour occurring to that at the water-air interface. This finding is critical for understanding that the loading imparted on submerged structures is significantly higher in free-water scenarios than it is at the extremes.

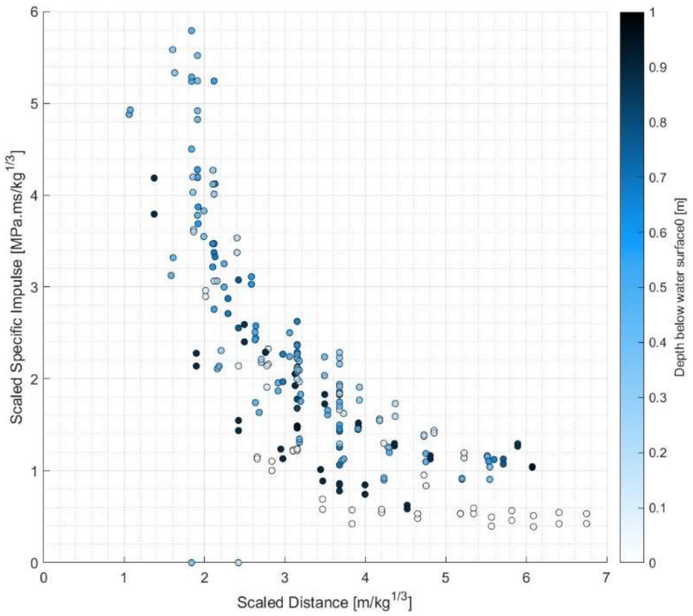

Figure 8 – Scaled max specific impulse values against scaled distance with marker colour indicating the depth at which the pressure gauge is below the

Floating Charge Conditions – Increased Variability

Of interest was the behaviour of shock wave propagation within the water medium when the explosive charge was floating on the water surface rather than being fully submerged. Figure 9 represents this behaviour with gauge measurement positions being 100mm down from water surface and at 500mm and 700mm standoff distances. Interesting here is the increased uncertainty between three trials which is deduced to be a direct result of the exact level of the water surrounding the floating charge as this was difficult to measure from externally of the tank. In the blue and red traces, there is comparable data, with peak pressures agreeing with one another at both standoff distances and the differences in arrival time being within experimental tolerances (~30mm based on 1477m/s evaluated from Figure 6a). The black traces however present enough evidence that in this trial, over half of the spherical charge was external of the water medium, meaning less energy transferred to the water itself despite the arrival time of shock agreeing with the other traces – a direct result of travelling at the sound speed of the water. The fundamental finding here is that the maximum overpressures recorded here are around 50% of that predicted using the curve fit predictor in Figure 6b, which suggests that half of the overall energy was released to the air in-line with expected experimental behaviours. This means that blast events from floating charges have a significantly lower load on submerged structures, although further work is required to confirm this to a higher degree of certainty.

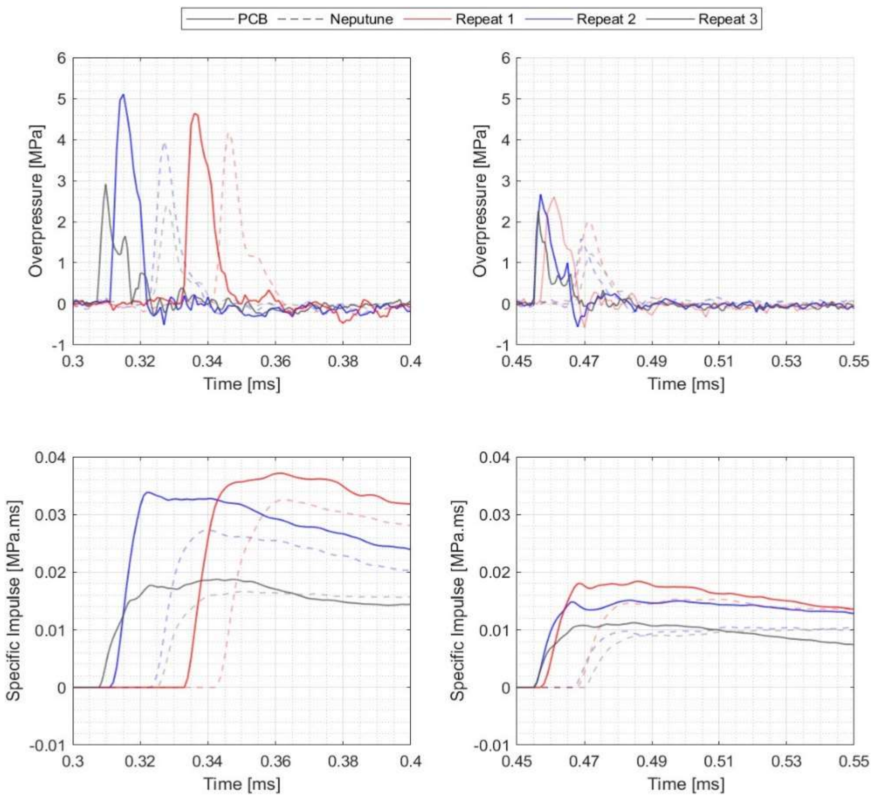

Figure 9 – Comparative results between both gauge type measurements at 500mm (left) and 700mm (right) standoff distances, located at a 100mm depth, where the charge was floating on the water surface

Conclusions

This article presents a benchmarking experimental study for characterising both free-water and shallow water blast waves for both submerged and surface-floating small-scale explosives. Presented are two prediction curves for arrival time and peak overpressure of submerged explosives with respect to a scaled distance away from the detonation epicentre, evaluated from optimising curve fits through 341 individual pressure-time histories recorded within this test series. The conclusion to these trials was regardless of charge and/or gauge location, the shock was governed by the physical properties of the water and was limited to the acoustic speed of wave within water being ~1480m/s established in Figure 6a. The influence of boundary condition proximity to gauge position was investigated and showed that the worst case loading conditions for a underwater explosion (when only considering the propagating shock and not subsequent bubble phenomena) is when in free-water conditions. When charges were located at the water surface, an increased variability in the pressure-time histories were presented, directly related to the exact position of the charge on the water surface. The global reduction in loading across all three trials when compared to the fully submerged results suggests that the pressure experienced within the water medium is a function of the charge mass beneath the water surface. Future trials are planned to validate the behaviours presented across wider mass-scales of explosives and explore the behaviour of response of submerged structures.

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