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CHARACTERISATION OF ACOUSTIC FIELDS GENERATED BY UXO REMOVAL
PHASE 5 QUARRY TRIALS OF ECS LOW-ORDER TECHNOLOGY

(BEIS OFFSHORE ENERGY SEA SUB-CONTRACT OESEA-22-142)

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Characterisation of acoustic fields generated by UXO removal Phase 5B quarry trials of ECS low-order technology

(BEIS Offshore Energy SEA Sub-Contract OESEA-22-142)

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ABSTRACT

This report describes the work undertaken in the project *Characterisation of acoustic fields generated by UXO removal: Phase 5*. The aim was to investigate the effectiveness of low-order shaped charge technology supplied by ECS to reduce the acoustic output from UXO disposal compared to high-order detonation by conducting controlled experimental trials in a flooded quarry test facility (Limehillock Quarry). This work was funded by the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) through the Offshore Energy Strategic Environmental Assessment programme (OESEA), Sub-Contract OESEA-22-142.

A total of 7 explosive tests were successfully conducted. These comprised two high-order tests on two sizes of surrogate munition (2.5 kg and 5.0 kg), two small shaped charges alone (35 g), and three small shaped charges (35 g) used as low-order deflagration charges against the larger surrogate munitions (two of 5.0 kg, one of 2.5 kg). All charges were detonated successfully and the acoustic radiated noise measured.

The results show that the use of the low order technique is beneficial due to the significant reduction of acoustic levels. The results demonstrate that the low order charges used can achieve a reduction in peak sound pressure level of between 14 dB and 19 dB and in Sound Exposure Level of between 14 dB and 22 dB compared to high order detonation for charge sizes of 2.5 kg and 5.0 kg. Post-shot observations and weight measurements suggest that only a modest amount of the surrogate munition charge was consumed during the deflagration shots on the larger surrogates.

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1 INTRODUCTION

1.1 BACKGROUND

The location and spatial size of many offshore wind farm developments and cable connector projects means there is a high potential to encounter unexploded ordnance (UXO) during construction. This is particularly so in the southern North Sea and Irish Sea due to overlap with World War I and World War II conflict areas, military training areas and munitions disposal sites, but it is relevant also in Scottish waters [Davies, 1996; Detloff *et al*., 2012; Eitner and Tröster, 2018]. As part of development planning, detailed surveys are undertaken to identify possible UXO and confirm what action is needed to reduce health and safety risks to a tolerable level. When UXO cannot be avoided or safely removed, detonation on site may be necessary (subject to obtaining required licences).

A common method used for the disposal of UXO is the deliberate detonation initiated by a small donor charge placed on the munition to initiate an explosion of the main charge (Cooper, 1996; Sayle *et al*.,
2009; Albright, 2012; Aker *et al*., 2012; Cheong *et al*., 2020). This can be achieved in a number of ways, and recent work has shown that the use of deflagration (internal combustion initiated using small-shaped charges) can reduce the severity of the detonation and offer the possibility of lower source levels. High-order underwater detonations of explosives can produce some of the highest sound pressures of all anthropogenic sound sources with the potential to cause fatal injury to marine mammals and other marine fauna in close proximity to the blast, but also auditory damage and behavioural responses at much longer ranges. (Sertlek *et al*., 2019; Merchant *et al*., 2020, Yelverton *et al*., 1973; Ketten *et al*., 1993; Dahl *et al*., 2020; Todd *et al*., 1996; Finneran *et al*., 2000; Danil and St. Leger, 2011; Sundermeyer *et al*., 2012; von Benda- Beckmann *et al*., 2015; Parsons *et al*., 2000; Salomons *et al*., 2021, Siebert *et al*., 2022; Robinson *et al*., 2022; Jenkins *et al*., 2022 ; Smith *et al.,* 2022).

Impulsive sounds of very high amplitude also present challenges for effective mitigation, with potentially large exceedance areas for commonly-used exposure thresholds (Finneran and Jenkins, 2012;
Popper *et al*., 2014; NMFS, 2018; Southall *et al*., 2019). Common mitigation strategies involve the use of spatial and temporal restrictions on the activity, visual and passive acoustic monitoring, and the introduction of additional noise of lower amplitude to create an aversive reaction by use of Acoustic Deterrent Devices (ADDs), and by use of small “scare” charges (JNCC, 2010; Merchant and Robinson, 2020, Robinson *et al.*, 2022). Noise abatement technologies have also been employed including the use of bubble curtains to attenuate the radiated sound (Loye and Arndt, 1948; Domenico, 1982; Schmidtke, 2010; Schmidtke, 2012; Croci *et al*., 2014; Bohne *et al*., 2019). In recent years, there has been a focus on alternative methods of disposing of UXO (Koschinski, 2011; Koschinski and Kock, 2009; Koschinski and Kock, 2015) including the use of low-order techniques such as deflagration, a method that until recently has been more commonly used for military EOD operations where a small, shaped charge creates a plasma jet which penetrates the UXO casing and initiates a low-order combustion (Merchant and Robinson, 2020; ESTCP, 2002). Deflagration has been shown to produce substantially reduced levels of radiated sound in controlled experiments compared to high-order detonations (Robinson *et al*., 2020), but as yet such low-order techniques have been infrequently used offshore.

The JNCC guidelines (2010) focus on minimising the risk of physical trauma and permanent auditory injury (PTS). The distance at which detonations could cause physical injury must be established as part of a noise risk assessment to inform the licensing process and estimate the effectiveness of mitigation measures. The NMFS thresholds (NMFS 2018) and those of Southall *et al.* 2019 incorporate the latest research results and provide an update of the Southall *et al.* 2007 thresholds referred to in the guidelines, and have been adopted by Statutory Nature Conservation Bodies

(SNCBs). Estimates of PTS injury zones to NMFS thresholds have resulted in much larger impact ranges than were previously estimated, extending in the most extreme cases well beyond any effective mitigation zone (e.g. up to 15 km from detonation for a UXO charge of >700 kg). Such results raise grave concerns for the protection of the marine environment and for industry, as the consequence of a risk assessment concluding that an UXO detonation is likely to result in a large PTS injury zone is onerous.

Underwater explosions as sources of sound have been the subject of considerable scientific study since the 1940s, both theoretically and experimentally (Cole, 1948; Arons, 1954 and 1970; Weston, 1960). The models developed in the above papers for deep water have been shown to agree reasonably well with experimental characterisation of explosive sources in shallow water environments (Gaspin and Shuler, 1972; Gaspin *et al*., 1979; Chapman 1985 and 1988; Hannay and Chapman, 1999; Soloway and Dahl, 2014; Wiggins *et al*., 2019), but there are limited experimental data available to describe shallow-water propagation over considerable distances for these sources, and few estimates of the acoustic output from explosive sources positioned on or below the seabed (NOAA, 2016; Salomons *et al*., 2021; Robinson *et al.,* 2022). It is acknowledged that source level estimates are highly uncertain, due to technical challenges and gaps in knowledge. Sound produced by the detonation of explosives is affected by various factors e.g. age, state of corrosion, design, composition, position, sediment type, degree of burial, orientation, and multiple device aggregation (Salomons *et al*., 2021, Robinson *et al.*, 2022). This leads to a high degree of uncertainty about the source noise level. Explosions are inherently a nonlinear source but most often a linear source is assumed. The transition to the region where the sound field may be considered to propagate linearly is not fully understood. The detonations generate acoustic waves which propagate on and through the seabed and a full understanding of this aspect of the propagation is currently lacking. In addition, measurement is ideally required of acoustic particle velocity to assess potential exposure of fish and invertebrates to the sound fields generated by explosions. Some of these issues are highly challenging and may take time to resolve fully.

1.2 INITIAL PROJECT PHASES

A series of projects have been undertaken with the overall aim to provide information to underpin more realistic exposure assessments at strategic and project levels, the identification of appropriate mitigation and guide EPS licence applications/decisions. The project series is titled *Characterisation of acoustic fields generated by UXO removal*. As with this current Phase 5 project, the work undertaken was funded by the UK Government's Department for Business, Energy and Industrial Strategy (BEIS) through the Offshore Energy Strategic Environmental Assessment programme (OESEA).

Phase 1 (OESEA-19-104) reviewed the scientific research in the field and the current operational procedures for UXO disposal, and provided initial guidance for offshore developers to gather acoustic data during UXO clearance operations.

Phase 2 (OESEA-19-107) included an experimental study to understand the acoustic 'near-field' of known explosive sources in the controlled environment of a flooded quarry and to characterise the effectiveness of deflagration as a sound attenuation mitigation method.

Phase 3 (OESEA-20-110) analysed a range of existing data (raw and interpreted) from offshore UXO clearance operations to evaluate the range and variability of measured and calculated acoustic metrics both from UXO detonations and those of donor charges, and scare charges (used as mitigation measures).

Phase 4 (OESEA-21-127) work measured the radiated noise levels from UXO disposal of a number of WW2 sea mines in the Baltic Sea undertaken by the Danish Navy using both high-order and deflagration techniques.

In addition, the partners liaised with UK Regulators and advisory bodies at periodic meetings to promote good practice in acoustic measurement of UXO clearance and to discuss the potential for use of alternative explosive ordnance disposal (EOD) techniques to minimise the environmental impact. Outputs of the project so far include:

- a guidance protocol was published for those undertaking measurements of UXO clearance in the ocean (including consultation with stakeholders) (Cheong *et al.,* 2020)
- a report for BEIS was published reviewing the scientific work in the field and describing all work undertaken in both Phase 1 and Phase 2 (Cheong *et al.*, June 2020)
- a journal paper was published (https://doi.org/10.1016/j.marpolbul.2020.111646) in Marine Pollution Bulletin describing a controlled experiment in a flooded quarry to measure the acoustic output during deflagration, with the results also presented at a stakeholder meeting at The Royal Society (Robinson *et al.,* 2020)
- a journal paper was published (https://doi.org/10.1016/j.marpolbul.2022.114178) in Marine Pollution Bulletin describing the acoustic characteristic of UXO disposal in the North Sea (Robinson *et al.,* 2022),
- the research findings for high and low-order disposal were presented at a number of international conferences such as Effect of Noise on Aquatic Life (Berlin, 2022), the International Conference on Underwater Acoustics (Southampton, 2022), and Oceanoise 2023 (Villanova, 2023).
- offshore measurements of deflagration during a sea-trial in coordination with collaborators and Danish Navy with measurement strategies building on the initial phases of the project (journal paper to be submitted).
- presentations made at a number of online meetings and fora (UK Underwater Sound Forum 2021, BEIS OESEA Research Seminar 2022) and to UK and US regulators and stakeholders.

For the Phase 5 work reported here, an Offshore Wind Innovation Exchange (OWiX) technology challenge (through the ORE Catapult) has led to four potential low order/low noise technologies being proposed for UXO clearance. Of the four systems only two were considered ready for field deployment and testing. The aim of the Phase 5 project is to test the efficacy and acoustic outputs of these two technologies in the flooded quarry test facility used in Phase 2.

1.3 SCOPE OF WORK

1.3.1 Introduction

In Phase 5, a controlled quarry trial was conducted to test currently available noise abatement technologies. The aim is to investigate the acoustic characteristics and other environmental effects generated when disposing of UXO using these methods. The five-day trial undertaken at the Limehillock Quarry facility was supervised by Thornton Tomasetti Ltd who supplied the explosives/surrogate munitions. The mitigation technologies were provided by the two client companies, the results of the experiments are reported separately.

1.3.2 Overall Scope

The technology tested here is based on a small low-order deflagration charge used to disable a munition without high-order detonations, using the type of shaped charge commonly used in low-order EOD methods. The low-order charges were produced and operated by ECS Ltd.

The project determined the acoustic output reduction using low-order charges compared to unmitigated high-order charges. The activities included:

- Short-range underwater pressure monitoring using low sensitivity underwater pressure gauges
- Far field acoustic monitoring of the low order and high order detonation.
- Spatial underwater noise measurement to determine received levels as a function of position

- Ambient underwater noise monitoring using an underwater recorder.
- Sound speed measurement using temperature sensor.

The acoustic data available for analysis includes:

- Received levels of all measurements made using the acoustic instrumentation including time waveforms and spectral content for measurements of sound pressure
- Determination of the source spectrum of the detonation and calculation of transmission loss as a function of acoustic frequency and distance from source

The trial took place at Limehillock Quarry facility at week commencing 14th November 2022, with the shock testing undertaken between 14th November to 16th November 2022.

2 EXPERIMENTAL METHODOLOGY

2.1 TEST FACILITY

The test facility is operated by Thornton Tomasetti Ltd, a multidisciplinary firm who specialises in structural shock testing using explosives and seismic airgun technology. Their main facility at Limehillock Quarry (near Keith in the northeast of Scotland) is the only UK inland underwater testing facility licensed for a wide range of test targets with access suitable for testing of naval structures to UK and NATO standards. Thornton Tomasetti operates a number of Shock Test Vehicles (STV) for use in underwater shock testing and their shock barge has an available test deck area of around 8.4 m x 4 m and a weight capacity of approximately 25 tonnes. The facility was used for a previous trial using deflagration charges reported elsewhere (Robinson *et al.,* 2020, Cheong *et al.,* 2020). As far as possible, the procedures detailed in the NPL Good Practice Guide (Robinson *et al.,* 2014) and the BEIS protocol were followed (though the latter are intended for offshore measurements (Cheong *et al.,* 2020).

The Limehillock Quarry facility is used extensively for in-water shock testing of structures for offshore marine applications and Thornton Tomasetti provided all the logistical support for the trial. The quarry has dimensions of approximately 250 m long by 125 m wide, is a little over 20 m deep on average and is filled with fresh water (Figure 4-1). The bathymetry between the position of the explosive source and that of the furthest hydrophone was 20.1 m ±1 m. During the trial, the average water temperature was stable at 8.6 °C for the shallowest 10m of the water column, but beneath this depth a thermocline can be observed with the temperature quickly decreased to 5.1 °C at the bottom.

Figure 2-1 Limehillock Quarry – hillside viewpoint

2.2 MEASUREMENT CONFIGURATION

Measurements of the acoustic pulse from each explosive source were recorded at two measurement stations with sensors suspended from the water surface. These were: (i) close to the source (nominally 10 m and 20 m) and (ii) at a distance of 147 m (at the far end of the quarry). The configuration and deployment may be seen in Figure 2-2. The main purpose of this test was to evaluate the effectiveness of low order deflagration techniques compared with high order detonations, and the methodology follows closely to that of a previous trial conducted at the same site (Cheong *et al.,* 2020, Robinson *et al.,* 2020).

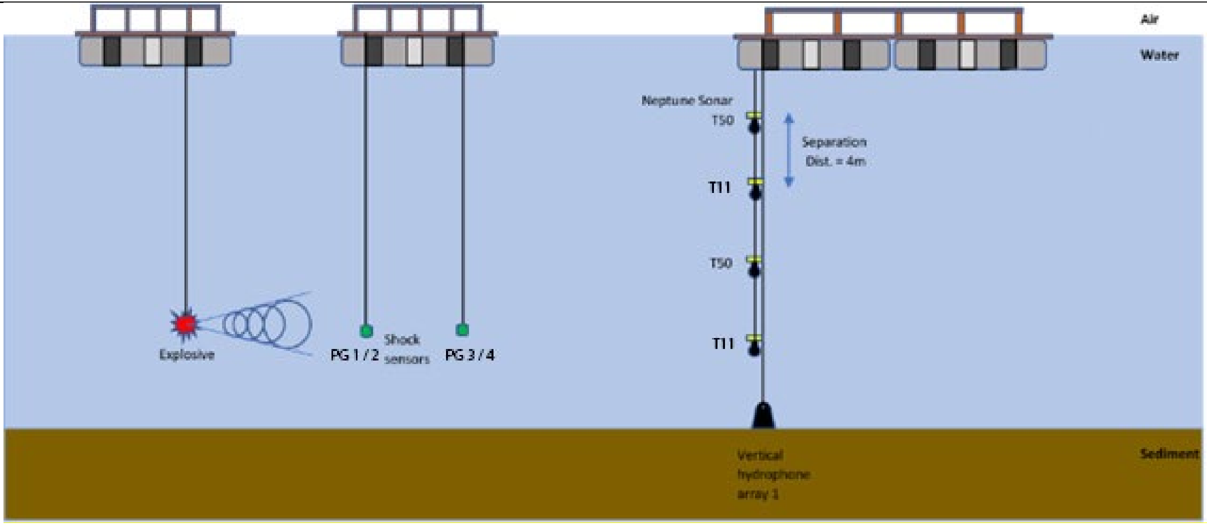

Figure 2-2 Schematic diagram of the measurement configuration in the trial (distances shown are not to scale).

Thornton Tomasetti provided the instrumentation to measure the nearfield response from the explosion which were deployed from shoreside station. NPL and Loughborough University provided the far field measurement equipment which consists of a four-elements vertical hydrophone array. This was deployed from a floating shock test vehicle (STV01) with an undercover area to provide weather protection to the data acquisition system and power supplies.

A sound particle motion sensor with bespoke underwater logger was also deployed to measure the particle motion of the signal from the explosive source. The sound particle motion measurements are not necessary for the characterization of the performance of the low-order technique (the key metrics being peak sound pressure level and Sound Exposure Level), but the opportunity was taken to obtain data using new instruments and the experimental results will be reported separately.

2.2.1 Sound pressure measurement

For the nearfield measurements, two types of underwater shock transducers were employed: T11 transducers (manufactured by Neptune Sonar, nominal charge sensitivity: 0.07 pC/kPa; maximum pressure: 275 MPa) and 138A26 transducers (manufactured by PCB, nominal voltage sensitivity: 0.29 µV/Pa; maximum pressure: 172 MPa). The shock transducers were powered by a PCB 482C05 four-channel unity-gain signal conditioner with additional PCB 422E06 charge amplifiers being used for the T11 transducers. A 16-channel 1MHz Yokogawa DL750 data recorder was used for capturing the data. All data were sampled at 500 kilosamples per second giving a time base resolution of 2 µs. Each measurement was recorded for a duration of 5 seconds. The DL750 data acquisition system was triggered by a 'Charge Probe' which is fixed directly to the explosive and provided a voltage step at the time of detonation. The shock pressure sensors were suspended from floating pontoons (Figure 2-4) and due to a minor re-positioning of the source between detonations, their separation distances varied slightly between measurement sets. The distances were measured on the surface with a laser rangefinder (confirmed by the acoustic propagation delay). All four sensors were deployed at 7 m water depth, the same depth chosen for all of the source charges.

For far field measurement, a four-element hydrophone array was deployed from Thornton Tomasetti's shock test vehicle STV01 (Figure 2-3). The array consisted of two T50 hydrophones (manufactured by Neptune Sonar, with nominal sensitivity 28 µV/Pa) and two T11 shock sensors (manufactured by Neptune Sonar, nominal charge sensitivity: 0.07 pC/kPa; maximum pressure: 275 MPa). The line array was configured with only low-sensitivity hydrophones to avoid system saturation due to the expected high amplitude pulses generated during the high-order detonations. In addition to these acoustic sensors, a Soundtrap ST300 (manufactured by Ocean Instruments, with high gain nominal sensitivity -186 dB V/µPa) underwater recorder was deployed at mid-water column for the duration of the trial to determine the background noise level. The acquisition was made using a PicoScope 4824 sampling at 10 mega-samples per second (time resolution of 0.1 µs) recording for 5 seconds triggered electronically based on the level prediction of the charge size of the explosive.

Figure 2-3 [Left] Near field pressure gauge deployment pontoons; the buoy is used to mark the position of the explosive. [Right] Far field acoustic array deployment on a floating shock test vehicle STV01.

NPL and Loughborough University instruments were completely independent and recorded by two different digitisers simultaneously providing some redundancy in order to avoid data loss by unexpected system failure.

The line-array hydrophones were calibrated traceable to national standards in the laboratory before the trial using the methods described in IEC 60565 (IEC 60565 2019 and 2020, Hayman *et al.,* 2017). This was done by comparison in a closed coupler in the range 5 Hz to 315 Hz. Free-field reciprocity was used to calibrate the T50 hydrophones over the frequency range 750 Hz to 200 kHz. Before and after deployment, the hydrophone sensitivities were checked at 250 Hz by use of a portable calibrated pistonphone (this enabled a full system sensitivity check as recordings were made on the acquisition systems of signals of known sound pressure level.

The sampling equipment was configured with the appropriate sensor sensitivities to ensure that as far as possible each individual system was configured to capture the acoustic waveform without distortion (including the high amplitude impulsive signals present during high order detonations). Preliminary calculations were performed to evaluate the likely sound levels to ensure the measurements can be carried out distortion-free. Background noise measurements were acquired before and after the test activities using a Soundtrap recorder, to allow the determination of the absolute noise level against background conditions.

2.2.2 Preparation of explosive sources

This objective of this test is to evaluate the acoustic characteristic of the deflagration charge similar to a previous trial conducted (Cheong *et al.,* 2020, Robinson *et al.,* 2020) at the same location. In order to simplify the measurement, the test regime was replicated as much as possible to allow direct comparisons. The tests consisted of two phases of detonation testing: high order tests, followed by low order (deflagration). Of the five low-order charges, three were used to deflagrate a surrogate munition (2 x 5 kg and 1 x 2.5 kg), one was fired alone, and one was placed against a metal plate. The charges detonated were as follows:

High order detonations (surrogate munitions/shells):
- 1 x 5kg charge
- 1 x 2.5kg charges

Low order detonation (deflagration):
- 2 x 5kg charges with 35g shaped charge
- 1 x 2.5kg charge with 35g shaped charge
- 1 x 35g shaped charge – no surrogate munition
- 1 x 35g shaped charge against a flat metal plate

Table 2-1 Test parameters from Phase 1 (High Order) and Phase 2 (Low Order) detonation tests.

Description	Phase 1 (High Order)		Phase 2 (Low Order)				
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Date	14 Nov	14 Nov	15 Nov	15 Nov	16 Nov	16 Nov	16 Nov
Shot time	14:13	15:00	12:31	14:04	10:10	10:40	11:40
Shaped charge	NA	NA	35g PE4	35g PE4	35g PE4	35g PE4	35g PE4
Surrogate charge	5.0kg PE4	2.5kg PE4	5.0kg PE4 LO	2.5kg PE4 LO	None	5.0kg PE4 LO	None
Target	5kg casing	2.5kg casing	5kg casing	2.5kg casing	No Target	5kg Casing	Square Plate 10mm thickness
Detonation method	Shock Tube	Shock Tube	Shock Tube	Shock Tube	Shock Tube	Shock Tube	Shock Tube
Distance from charge float to STV01 Aft face (m)	149.0	149.0	151.0	151.0	149.0	149.0	149.0
Distance from charge float to PG1 / PG2 (m)	10.5	10.5	10.5	10.5	10.5	10.5	10.5
Distance from charge float to PG3 / PG4 (m)	20.5	20.5	20.5	20.5	20.5	20.5	20.5
Water depth at charge (m)	19.4	19.4	18.0-19.6	18.0-19.6	18.0-19.6	18.0-19.6	18.0-19.6
Charge depth (m)	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Low Order Burn Weight Achieved (after slug removed)	NA	NA	None, 5kg recovered	None, 2.5kg recovered	NA	None, 5kg recovered	NA

Thornton Tomasetti Ltd supplied the cased surrogate charges used as munitions in the deflagration tests and for the high order charges including the fabrication and provision of PE4 explosive, and the means of deploying and detonating at the firing point for all testing. For continuity, these were identical to those used in the earlier studies (drawings are shown in Annex 1). The deployment of deflagration charges and firing was handled by ECS to ensure the deflagration operation was conducted according to ECS operational procedures.

Each test took approximately 2-3 hours to allow safe deployment, recovery and required inspections pre- and post-test for high order detonations, subject to weather conditions. The number of munitions/charges and order of the munitions used was agreed with the operators prior to the start of the trial in order to prioritise the more important tests to ensure a comprehensive dataset. It should be noted that not all test charges were detonated according to the test plans due to limited time available;

the repeat shots of a 2.5 kg surrogate, 35 g shaped charge only and 35 g shape charge against a flat plate were removed due to time restraint.

The detonation test for ECS took place between 14th November to 16th November 2022 and the test schedule and associated details are described in Table 2-1 above.

2.3 HIGH-ORDER CHARGES (SURROGATE MUNITIONS)

The surrogate munition casings were cylinders of approximate diameter 200 mm and length 600 mm and had end caps secured with external bolts. The explosive filler was a plastic explosive (PE4) which consisted of 88% RDX plastic explosive (Grade 1A), 11% plasticiser and 1% penta-erythritol dioleate. PE4 is a common and relatively insensitive hand-mouldable general-purpose plastic explosive which may be used underwater, and ignites at 218 °C. The surrogate cylinder was designed by Alford Technologies Ltd (www.explosives.net) and was first used in 2019 deflagration trial (Cheong *et al.,* 2020, Robinson *et al.,* 2020), subsequently the same cylinder design is permitted to be used in this test to minimize errors in the acoustic output. The design of the surrogate munition can be found in Annex 1.

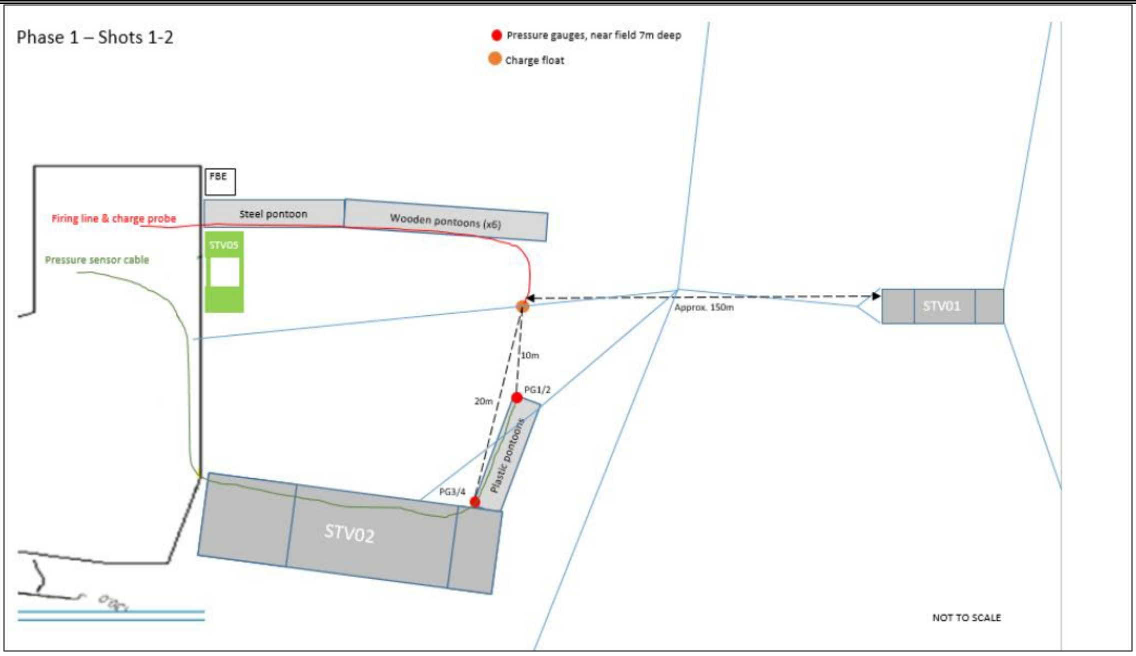

Figure 2-5 High order test configuration

For the high order tests, the surrogate shell was suspended from a float via 3 mm diameter steel wires. The wires were measured to ensure that the charge was always at 7 m depth, which included the depth of the float submerged under the weight of the charge and charge casing. Figure 2-5 shows the test configuration of the high order tests.

High order charges are reasonably well characterised when suspended in mid water column and the previous study showed good agreement with the classic models in the scientific literature [Arons 1954; Weston 1960]. Only 2 high order charges were tested for validation purposes. A 5kg and a 2.5kg charges were detonated using a shock tube. No casings or other material were recovered from these tests; all materials were destroyed as a result of the high order detonations.

2.4 LOW-ORDER CHARGES

The low order method is based on the use of a shaped charge to initiate deflagration of a UXO target. The product used here is the LX-30 WASP low order deflagrator (Figure 2-6), designed and manufactured by ECS (see: https://www.loworder.co.uk/products). The device is designed to be a self-filled shaped charge. In this trial, 35 g of PE14 explosive were used throughout the deflagration phase to ensure consistent output. The device works by penetrating an UXO target and combusting the explosive inside and neutralising it. Figure 2-7 shows how the shaped charges were attached to the targets during the deflagration test.

Figure 2-6 ECS LX-30WASP Low order deflagrator

For the deflagration test, because there is some remnant explosive after a deflagration event, a large steel debris catcher was suspended via a floating moonpool structure several metres directly beneath the test munition to capture any escaping explosive material (and prevent it reaching the quarry bed). The debris catcher is required for safety reasons by the quarry operator to recover and remove any active explosive material from the quarry. A crane was used to lift the debris catcher into the moonpool from which it was suspended using steel lifting wires. Figure 2-8 shows the test configuration of the low order test and Figure 2-9 shows a 3D schematic of the debris catcher for recovering the surrogate remnant after each test.

After each test, the surrogate casing was recovered to inspect the surrogate, weight the remaining explosive and discard/remove remaining charge slugs and explosive to make ready for the next test. Any remains of the PE4 explosive were collected and incinerated at the end of the trial.

2.5 OBSERVATIONS OF LOW ORDER TESTS

It was noted upon recovery of the remnant surrogate that the casing remained intact. Although the shaped charge penetrated the end plate to the PE4 explosive, it was not clear whether the deflagration process was fully initiated during the test. The weight of the surrogate PE4 was measured after each recovery by scraping all the PE4 explosive from the surrogate casing. The different in weight before and after the deflagration test was very modest as reported in Table 2-1 (final row). This applied to all 3 surrogate shells in the deflagration tests. This suggests that the shaped charge may not have fully initiated a deflagration of the explosive inside the surrogate munition. Figure 2-10 and Figure 2-11 show the states of the surrogate after recovery. The cylinders remain intact which differed from the original study where deflagration was successfully initiated and the end caps of the casing were blown out and a significant quantity of explosive had been combusted.

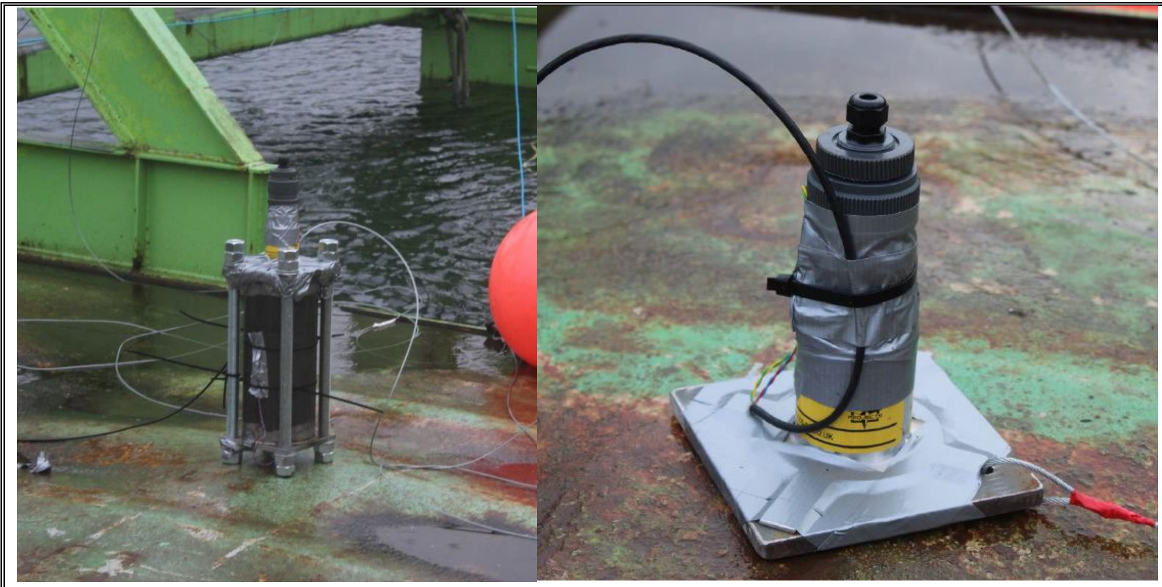

Figure 2-7 [Left] Shaped charge attached to 5kg surrogate cylinder (test 3). [Right] Close up image of the shaped charge attached to a steel plate (test 7).

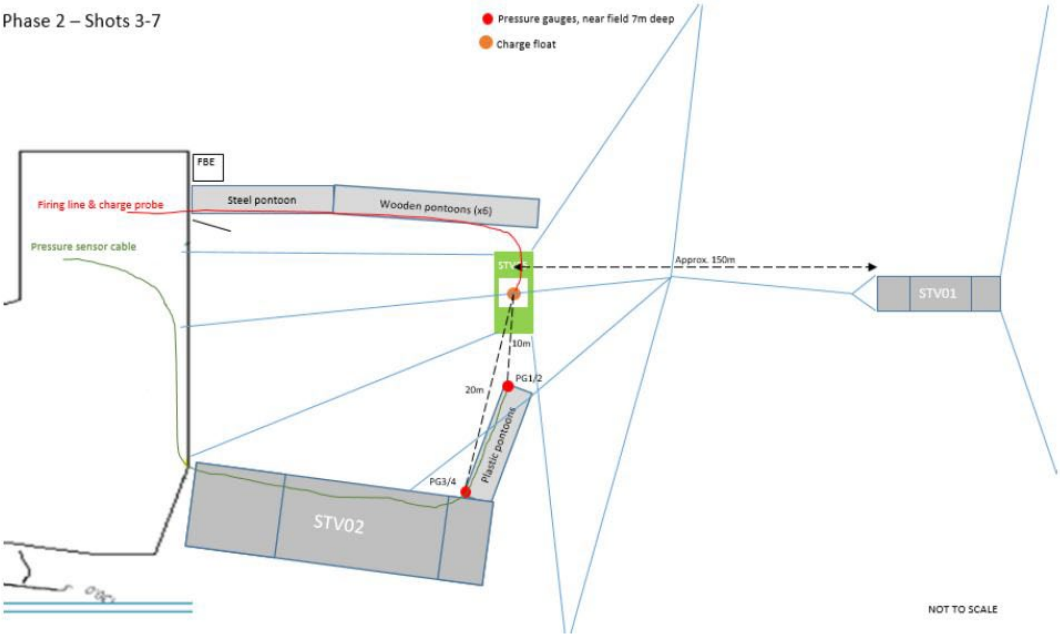

Figure 2-8 Low order test configuration with the deployment of the debris catcher.

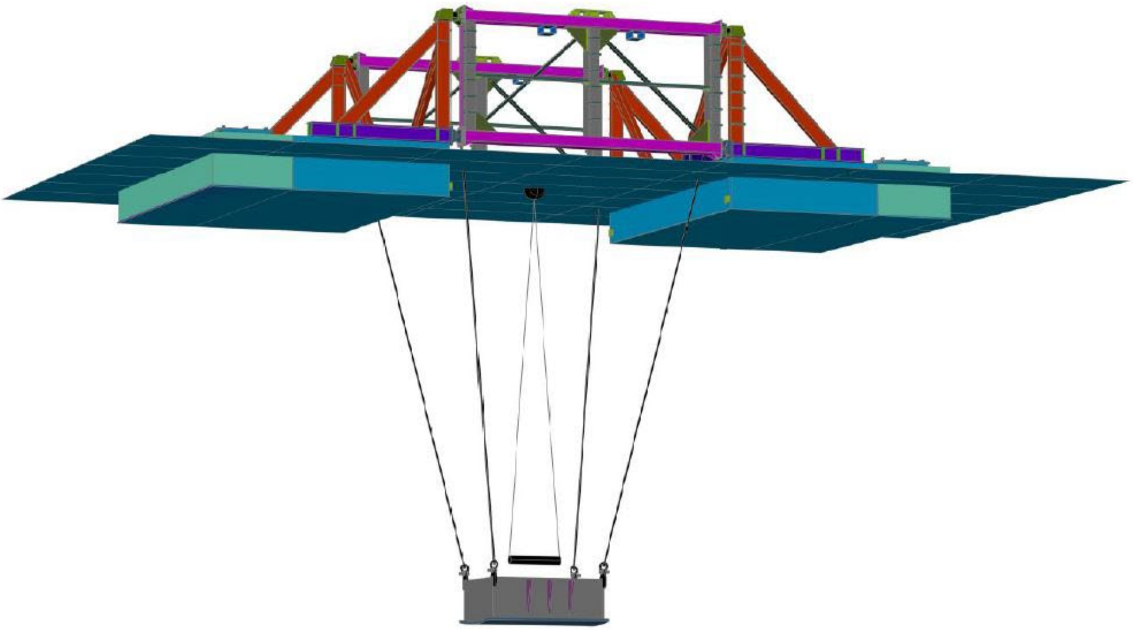

Figure 2-9 Debris catcher deployed for recovery of surrogate after deflagration test.

However, it should be noted that the previous study conducted on deflagration (Cheong *et al.,* 2020, Robinson *et al.,* 2020) showed that the acoustic output relies entirely on the shaped charge size, and the peak sound pressure is primarily generated from the shock created by the explosion from the shaped charge explosive (the size of the munition and the degree of combustion having no influence on the peak sound pressure). Therefore, it was expected that the acoustic output would be dominated by the 35 g PE4 explosive used in the shaped charge. The fact that deflagration may not have initiated would not invalidate the acoustic analysis in terms of the peak sound pressure. The sound exposure level may be slightly underestimated due to the absence of the low level components from the slow burning process.

Figure 2-10 [Left] 5kg surrogate shell recovered after deflagration Test 3. [Right] PE4 explosive after deflagration Test 3.

Figure 2-11 [Left] PE4 explosive inside of 2.5 kg surrogate shell after deflagration Test 4. [Right] PE4 explosive inside of 5 kg surrogate shell after deflagration Test 6.

3 RESULTS

3.1 TIME DOMAIN WAVEFORMS

The time waveforms received by the NPL hydrophone are shown in Figure 3-1 for the ECS tests. The hydrophone was 147 m from the explosions. There were 7 shots in the tests, two of high order and 5 of low order. The high order ones were using charges of 2.5 kg and 5 kg. Five shaped charges at 35 g were used on all low order detonations, three used on the 2.5 kg and 5 kg surrogate shells, one attached to a steel plate, and one was freely suspended.

There are three peaks in the two plots at the top row for the high order as shown in Figure 3-1. They were generated by the initial detonation of the donor charge, followed (consecutively) by two collapsing bubbles. There are two peaks with the low order explosions as shown in the plots in the second and third rows. They were from the initial explosion and the collapse of the first bubble. Only the first collapsing bubble is visible clearly in the four plots.

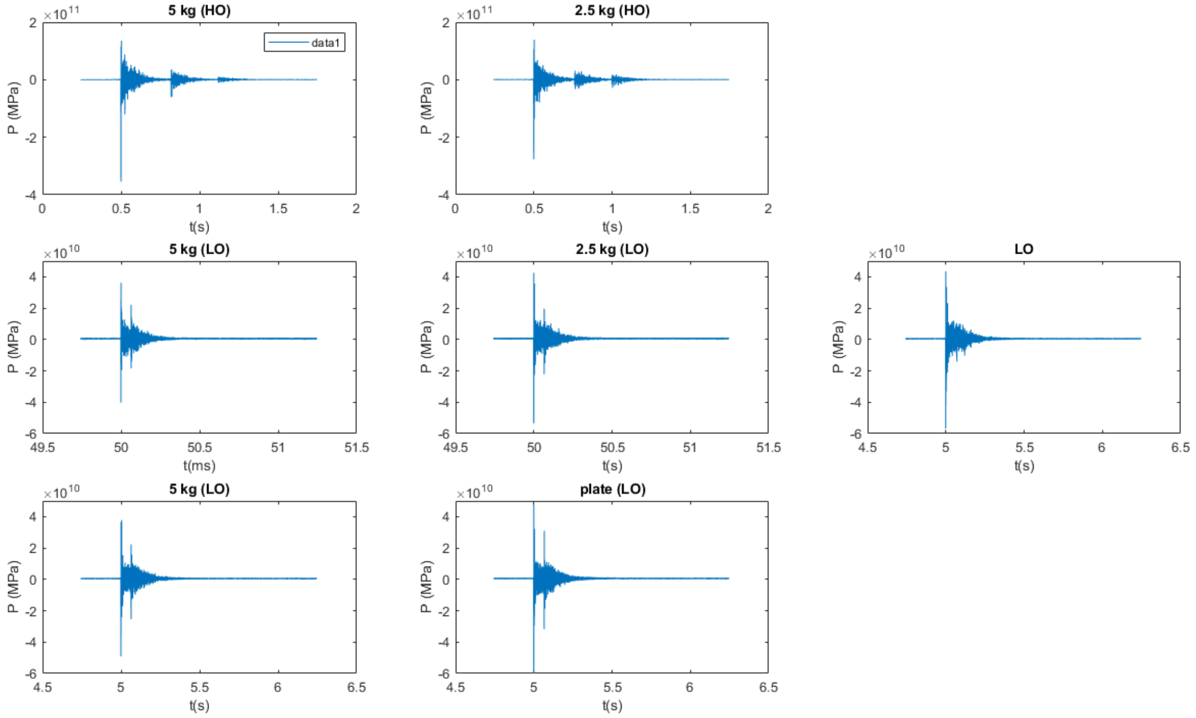

Figure 3-1 Time waveforms of measured signals with NPL's hydrophone at 147 m

The pressure waveform measured at close range with Thornton Tomasetti's pressure gauges are shown in Figure 3-2.

Only data from one pressure gauge at each range 10.5 m and 20.5 m were plotted since the results of the two at the same range were very similar to each other. The received signals are impulse-like at close range. The impulse spreads in time as clearly shown in the Figure 3-1 is mainly due to the reflections from the water surface and bottom (the temporal dilation of the pulse being due to the impulse response of the water channel). Compared with the third plot in the second row between Figure 3-1 and 3-2, the bubble peak is clearly visible at this close range.

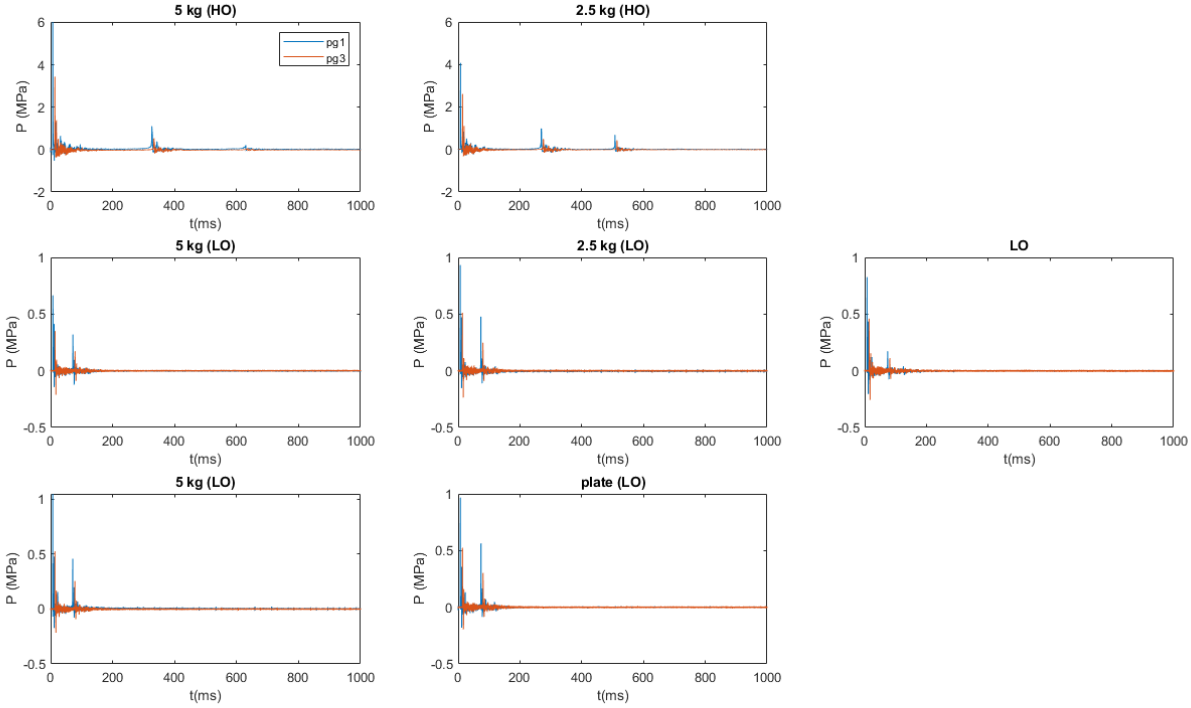

Figure 3-2 Time waveforms of measured signals with pressure gauge at 13 m

3.2 FREQUENCY DOMAIN SIGNALS

In the following analysis, the terminology used in ISO 18405 and ISO 18406 was used unless otherwise stated (ISO 18405 and 18406: 2017). The SPL is the root-mean-square average of the sound pressure over the pulse duration, the SEL is the level of sound exposure calculated over the pulse duration, and the peak sound pressure level (SPL_{pk}) is the level in decibels of the peak sound pressure in the pulse. The frequency averaged data are calculated in decidecade bands (ISO 18405) the correct nomenclature for what are effectively the same as classic one-third octave frequency bands when calculated using base 10 arithmetic (IEC 61260-1:2014).

The narrow-band sound pressure level (SPL) for the above signal waveforms is shown in Figure 3-3 with a frequency step resolution of 0.67 Hz (blue line) and in decidecade band from 2 Hz to 200 kHz (red line).

The figures from 3-4 to 3-10 show similar plots of the detailed narrow-band spectrum of SPL (in frequency steps of 0.67 Hz resolution), and the decidecade band data on the same plot for all four pressure gauge data sets from the seven shots for ECS tests. The high resolution data exhibits the expected very large fluctuations sound pressure level at high frequency end of the spectrum due to interference between frequency components. The decidecade band spectra shows a smoother response, the amplitudes being averaged over each frequency band (the bands being wider as the frequency increases).

Note that the receiver settings for the high and low order measurements were not the same. A very high sampling rate of 10 MHz was applied for the high order shots. Based on the video recording of an initial test provided by ECS before the quarry trial, it was expected that the deflagration of the ECS shaped charge could last a much longer time (several minutes), so that lower sampling rate at 125 kHz was used for the first two low order shots to allow a greater record length on the time recording. The sampling rate changed to 1.25 MHz for the last three shots once it was realised that the deflagration was not of such a long duration for the tests undertaken in this study.

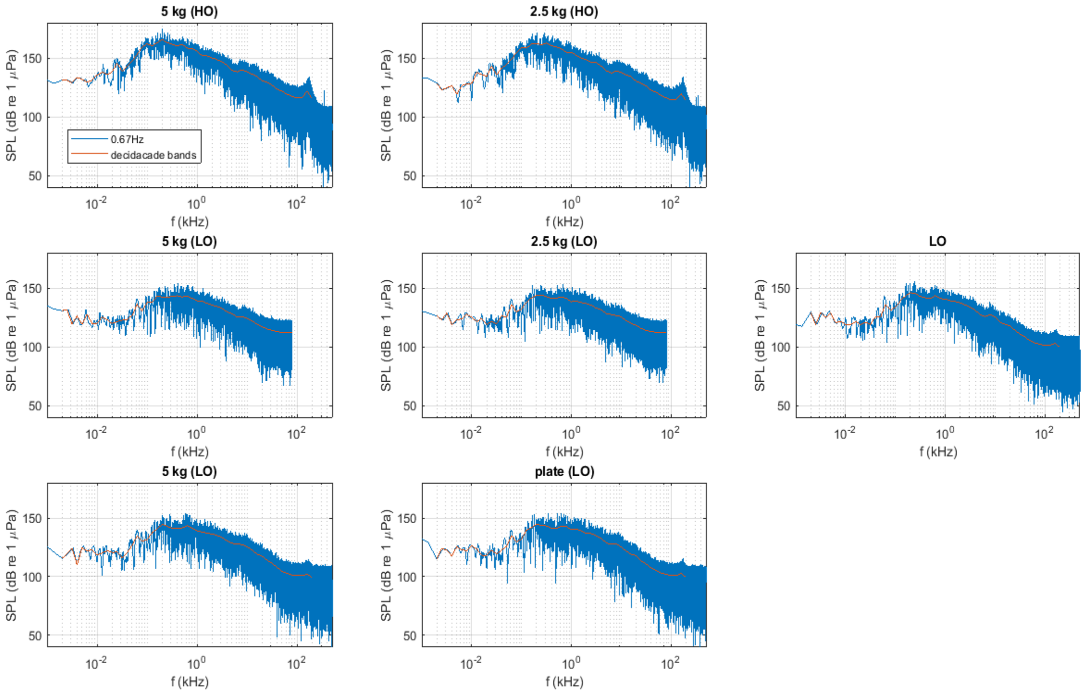

Figure 3-3 The sound pressure level (SPL) spectra for the signal waveform in Figure 3-1 in both narrow-band at 0.67 Hz resolution (blue) and decidecade bands (red).

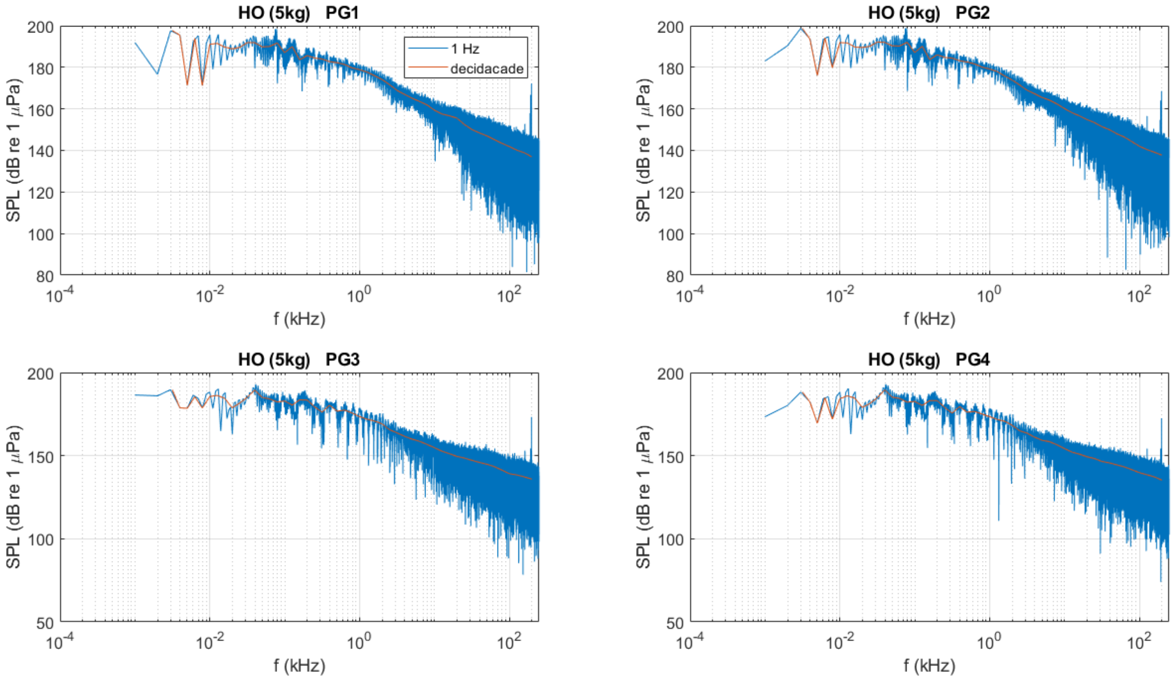

Figure 3-4 The sound pressure level (SPL) spectra of shot no. 1 in both narrow-band at 0.67 Hz resolution (blue) and decidecade bands (red).

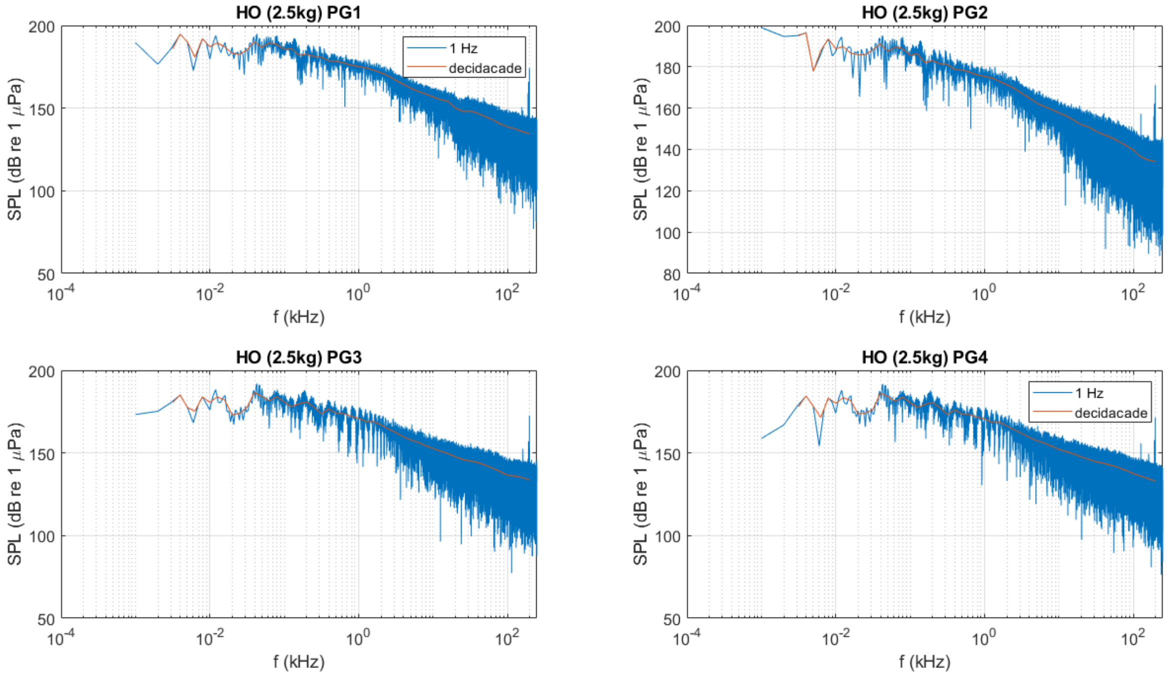

Figure 3-5 The sound pressure level (SPL) spectra of shot no. 2 in both narrow-band at 0.67 Hz resolution (blue) and decidecade bands (red).

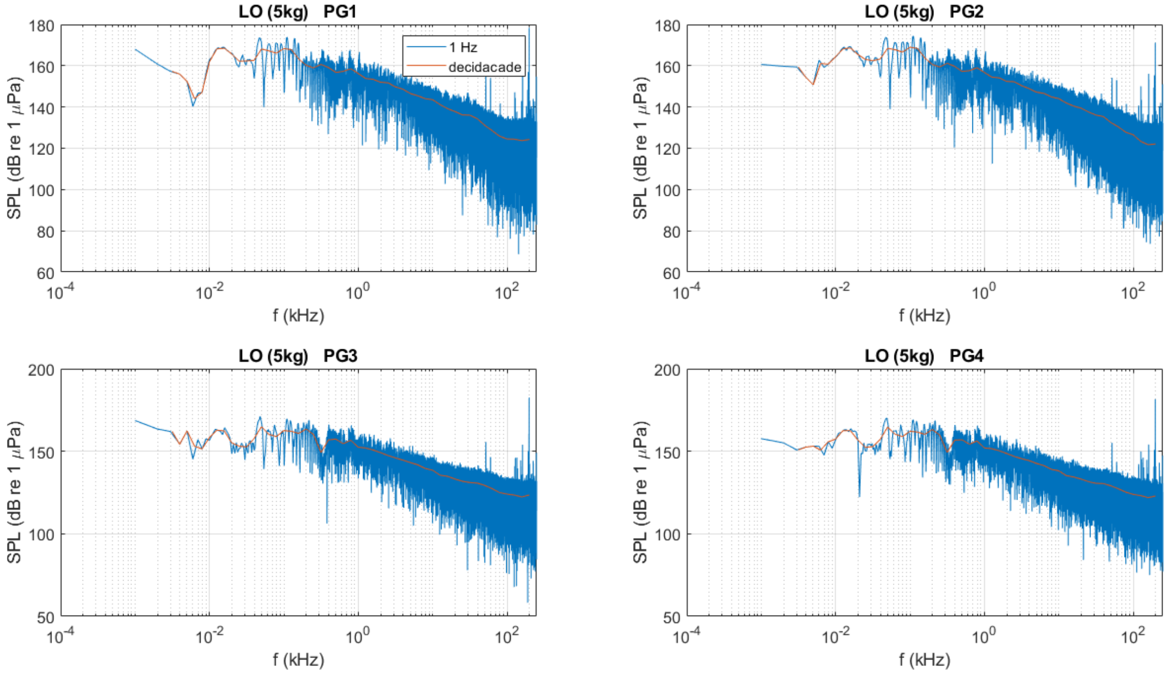

Figure 3-6 The sound pressure level (SPL) spectra of shot no. 3 in both narrow-band at 0.67 Hz resolution (blue) and decidecade bands (red).

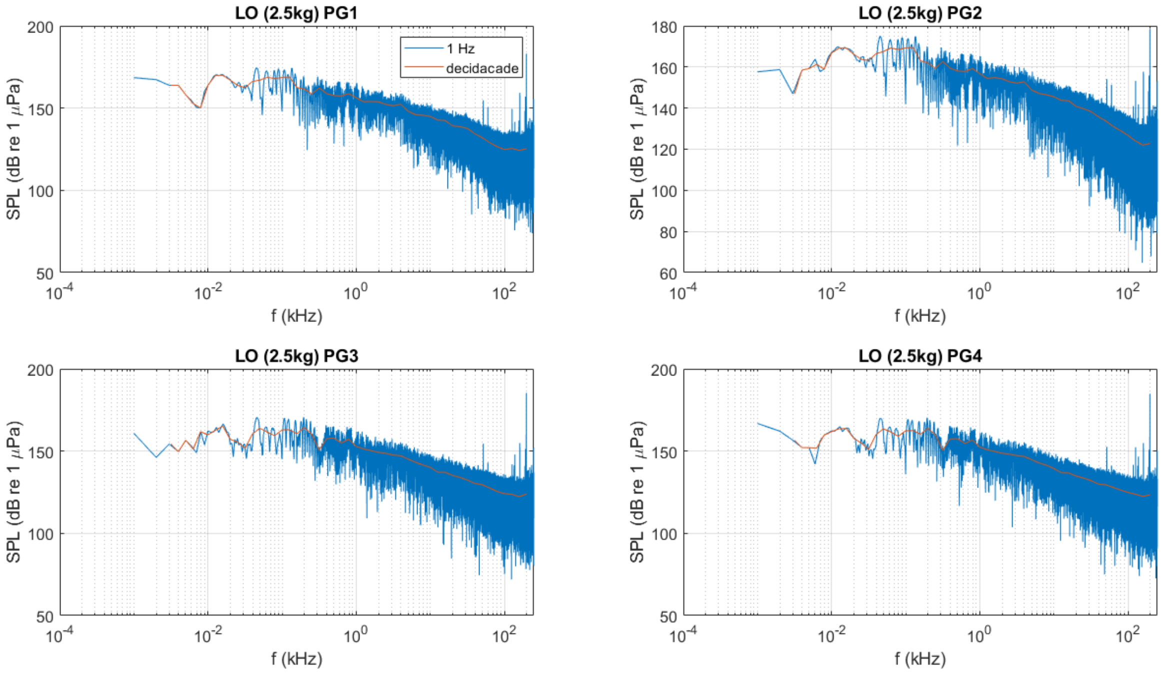

Figure 3-7 The sound pressure level (SPL) spectra of shot no. 4 in both narrow-band at 0.67 Hz resolution (blue) and decidecade bands (red).

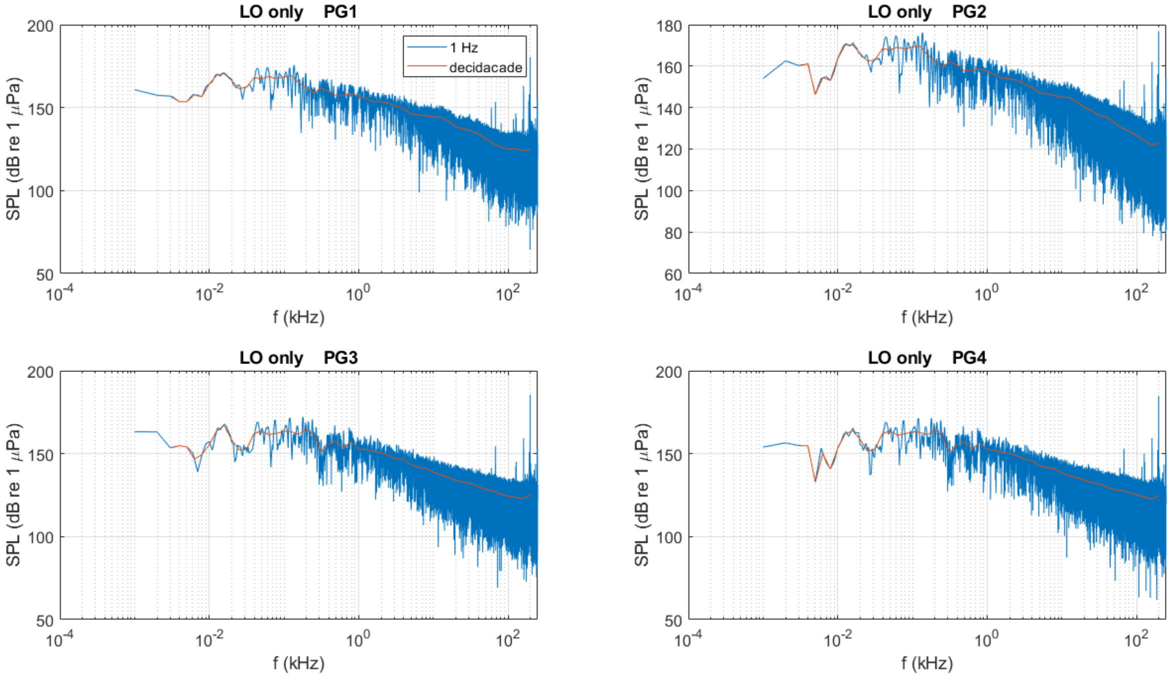

Figure 3-8 The sound pressure level (SPL) spectra of shot no. 5 in both narrow-band at 0.67 Hz resolution (blue) and decidecade bands (red).

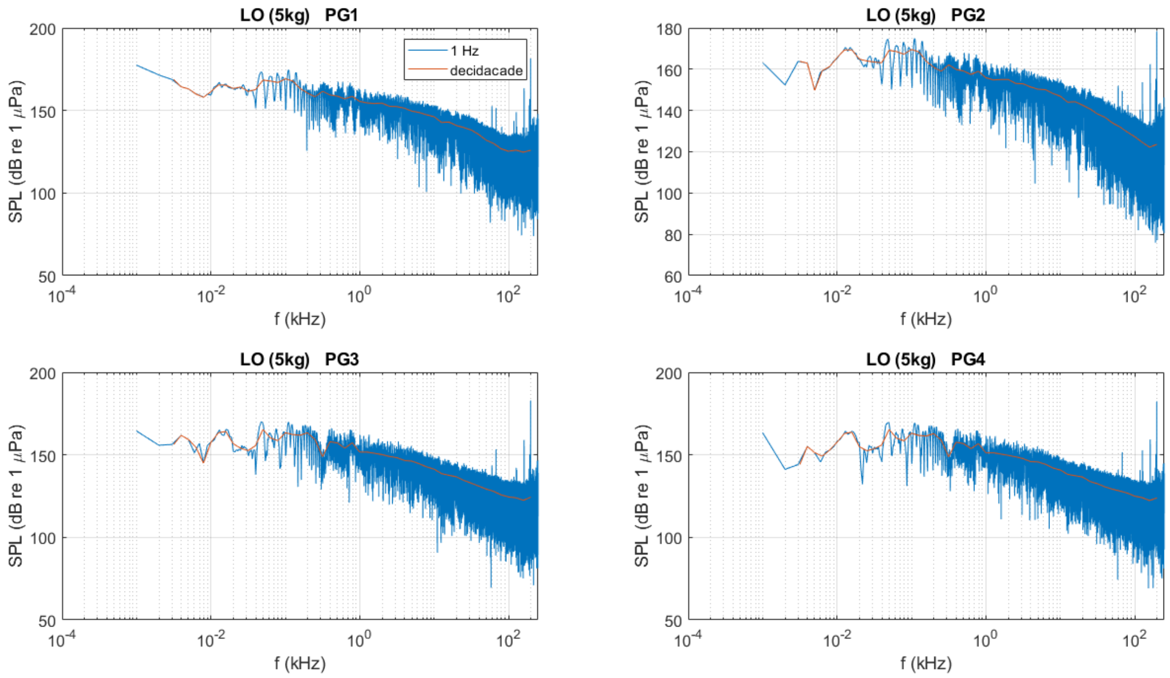

Figure 3-9 The sound pressure level (SPL) spectra of shot no. 6 in both narrow-band at 0.67 Hz resolution (blue) and decidecade bands (red).

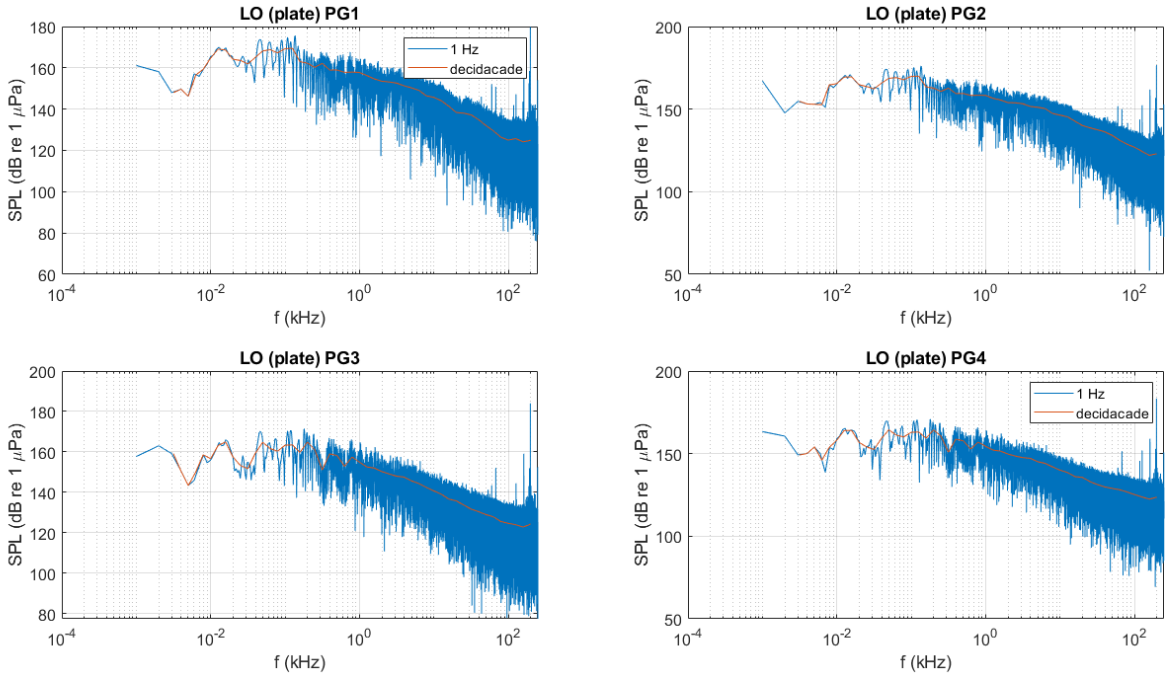

Figure 3-10 The sound pressure level (SPL) spectra of shot no. 7 in both narrow-band at 0.67 Hz resolution (blue) and decidecade bands (red).

3.3 REDUCTION WITH LOW ORDER CHARGES

The measured peak sound peak pressure level (SPL_{pk}) and sound exposure level (SEL) with the NPL hydrophones and the pressure gauges (PG) are listed in Table 3-1 and Table 3-2. They were measured at three distances between the explosion and the sensors: 10.5 m and 20.5 m for the pressure gauges, and 147 m for the hydrophones. The tabulated data are also plotted in Figures 3-11 to 3-14. The diamonds in Figures 3-11 and 3-13 are for the SPL_{pk} and SEL from the high order detonations, while the circles for the low order detonations.

Figures 3-12 and 3-14 show the measured SPL_{pk} and SEL as function of charge size. Model predictions are also plotted in blue and orange for comparison with the measurements. This is the same analysis presentation as performed for the previous low-order deflagration study (Robinson *et al.,* 2020). The two high order data sets are indicated with diamonds and circles, while the low order data are indicated with a square symbol. The level differences in SPL_{pk} between the low and high order are 16.8 dB between the high order explosion with the 5 kg charge and low order of deflagration of the same sized 5 kg surrogate shell as shown in the figure. The observed difference is 14 dB between the high order of the 2.5 kg charge and low order on the 2.5 kg shell. The level differences in SEL between the low and high order are about 19 dB between the high order of the 5 kg charge and low order of the 5 kg shell, and 17.4 dB between the high order of the 2.5 kg and the low order at 2.5 kg.

Table 3-1 Peak sound pressure level, SPL_{pk} (dB re 1 µPa) for ECS tests

	NPL	**PG1**	**PG2**	**PG3**	**PG4**	**Detonation type**	**Charge size**
Distance /Shot no	147	10.5	10.5	20.5	20.5		
1	231.0	255.6	256.5	250.7	250.0	High Order	5.0kg
2	228.8	252.2	253.6	248.3	247.5	High Order	2.5kg
3	212.1	236.5	238.2	230.9	231.4	Deflagration	5.0kg (35g)
4	214.6	239.4	240.3	234.2	233.9	Deflagration	2.5kg (35g)
5	215.1	238.3	239.7	233.2	233.1	Shaped charge	35g
6	213.8	240.4	241.7	234.4	234.6	Deflagration	5.0kg (35g)
7	215.9	239.7	241.1	234.4	234.0	Shaped Charge	35g + plate

Table 3-2 Sound Exposure Level, SEL (dB re 1 µPa^2s) for ECS tests

	NPL	**PG1**	**PG2**	**PG3**	**PG4**	**Detonation type**	**Charge size**
Distance /Shot no	147	10.5	10.5	20.5	20.5		
1	199.1	219.9	219.7	215.0	214.3	High Order	5.0kg
2	197.9	216.7	220.5	212.4	211.9	High Order	2.5kg
3	183.3	198.0	198.3	195.2	194.7	Deflagration	5.0kg (35g)
4	183.5	199.3	199.2	196.2	195.8	Deflagration	2.5kg (35g)
5	183.7	198.7	199.0	196.3	195.8	Shaped charge	35g
6	183.4	199.8	199.4	195.8	195.4	Deflagration	5.0kg (35g)
7	184.4	199.2	199.8	196.4	196.1	Shaped Charge	35g + plate

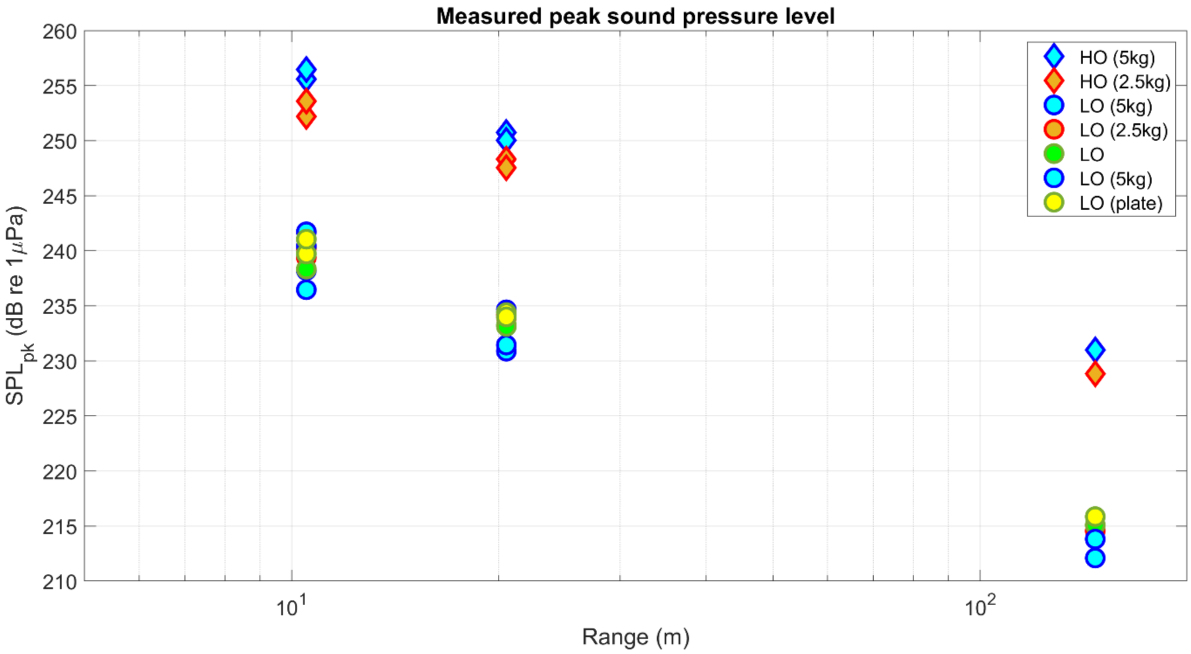

Figure 3-11 The peak sound pressure level (SPL_{pk}) for the seven shots measured at 10.5 m, 20.5 m and 147 m

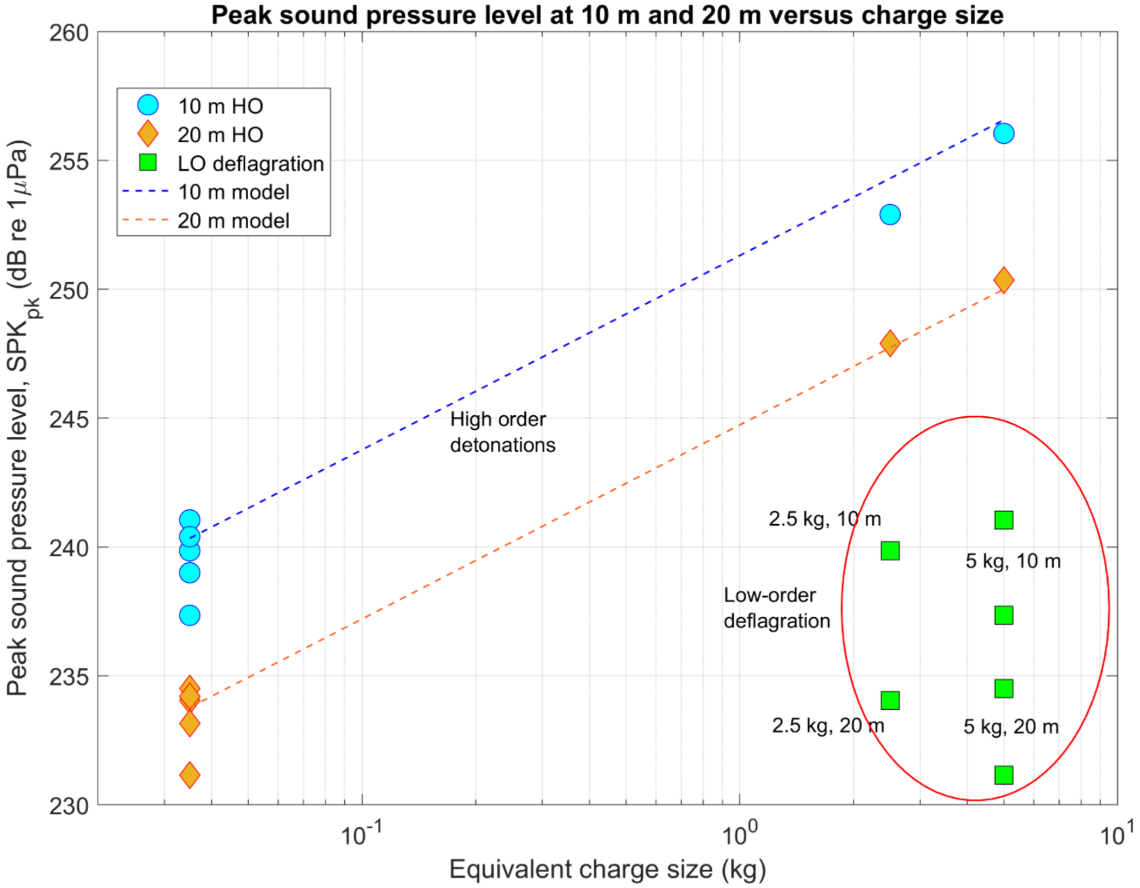

Figure 3-12 The peak sound pressure level (SPL_{pk}) versus charge size for 10.5 m and 20.5 m

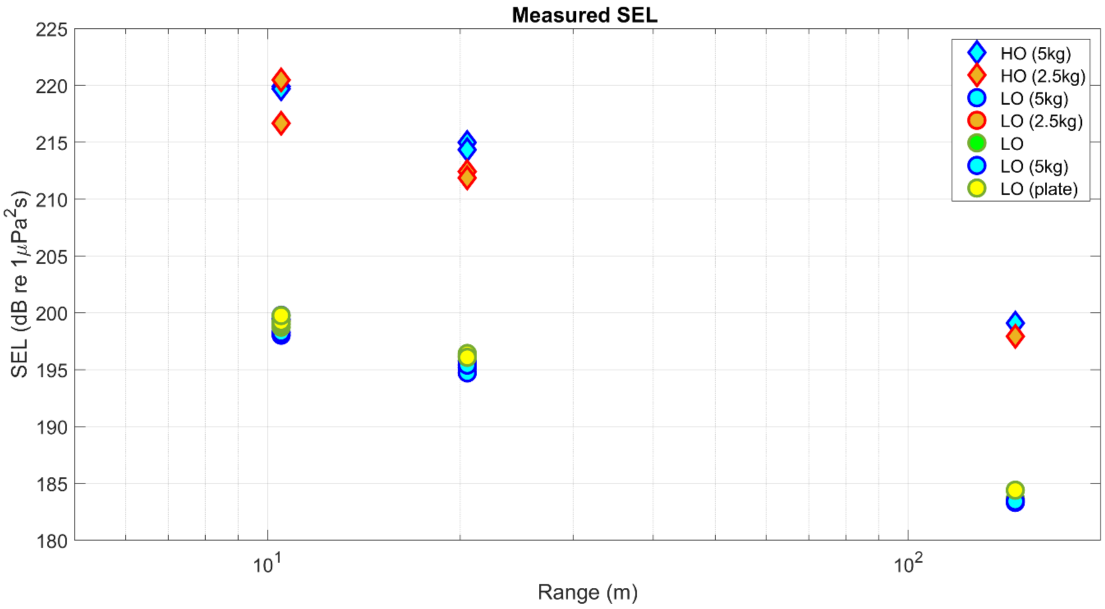

Figure 3-13 SEL for the seven shots measured at 10.5 m, 20.5 m and 147 m

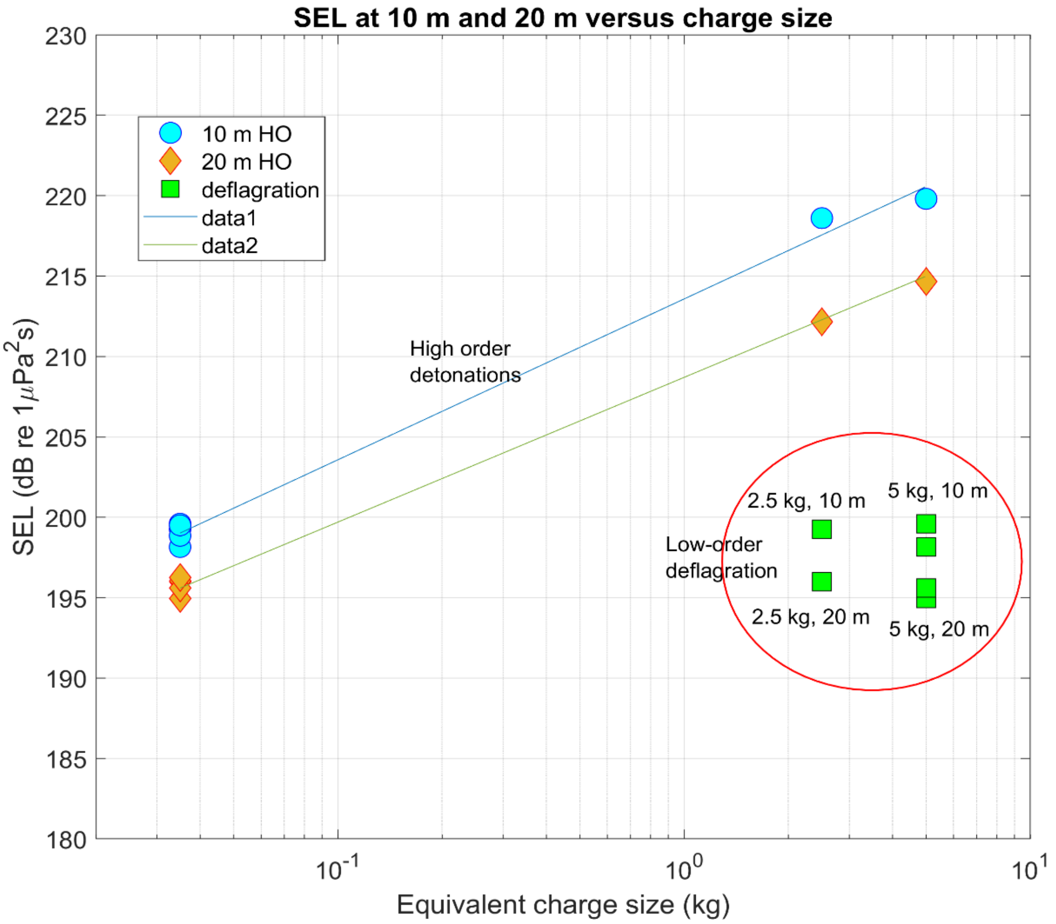

Figure 3-14 SEL versus charge size for measurements at 10.5 m and 20.5 m

The empirical models established by Arons, Cole, and Weston [Cole 1948; Arons 1954; Weston 1960] may also be used to predict the sound exposure as a function of scaled range as follows:

$$E = K_E\, W^{\frac{1}{3}} \left(\frac{W^{\frac{1}{3}}}{R} \right)^{\beta} \qquad (1)$$

where E is the sound exposure in $\mathrm{Pa}^2\mathrm{s}$, and W is the charge weight in kg, R is the slant range in meters, and K_E and β are determined empirically.

3.4 ANALYSIS OF RESULTS

The results of the measurements of peak sound pressure level for charges where deflagration was used are shown on the bottom right of Figure 3-12 plot in green symbols. They clearly show a much lower level than for the high-order detonations for the same charge size, with between 14 dB and 19 dB reduction in level (nearly a factor of 10 reduction in peak sound pressure). The results obtained for the shaped charges of 35 g size show that the levels obtained for the low-order deflagration charges are very close to those for the equivalent size of shaped charges when detonated alone (either free or against a metal plate).

The SEL, a metric commonly used in exposure calculations for marine fauna, is also substantially reduced when using deflagration charges. Figure 3-14 shows the SEL at nominal distances of both 10.5 m and 20.5 m calculated for a one second integration time plotted against charge size for all the detonations. Again, the results of the measurements of charges where deflagration was used are shown on the bottom right of the plot. The data clearly show a much lower level than for the high-order detonations for the same charge size, with between 14 dB and 22 dB reduction in SEL observed, with 20 dB equivalent to a factor of 100 in acoustic energy.

The results demonstrate that the low order charges used can achieve a reduction in peak sound pressure level and SEL of around 20 dB compared to high order for UXO charges of size 2.5 kg and 5.0 kg. The acoustic levels from this trial agrees with previous study where the peak sound pressure and SEL are scaled according to the shaped charge weight and not the size of the UXO (surrogate charge in this case). For the low-order case, the detonation of the small charge is the dominant source of acoustic pressure pulse created by the explosion.

The calculation of SEL is more challenging than the peak sound pressure level in the enclosed quarry because there are reflections from boundaries which arrive during the longer integration time used (one second). Estimating the peak sound pressure close to the source is not influenced by this because the shock front arrives first, and any time window used to isolate it is very short. The time for the SEL calculation was kept longer to include two pulses due to the gas bubbles produced by each explosion, and this inevitably includes reflections, for example from the water surface, and quarry bottom and side walls. This problem is likely to be worse for the measurements at greater distance from the source, and this is likely to contribute to the slightly poorer agreement with the model (Cheong *et al.,* 2020, Robinson *et al.,* 2020).

4 DISCUSSIONS AND CONCLUSION

4.1 SUMMARY

A total of 7 explosive tests were successfully conducted at Limehillock Quarry to determine the acoustic output during testing of a low-order technique for UXO disposal supplied by ECS Ltd.

The explosions comprised two high-order tests (charge sizes of 2.5 kg and 5.0 kg), followed by three small shaped charges (35 g) used for low order tests against large surrogates shells (two at 5.0 kg, one at 2.5 kg). In addition, two of the 35 g shaped charges were tested without surrogate shells, one freely-suspended and one against a metal plate. The experiment was designed to replicate the method used in the testing of low-order deflagration charges in a previous study (Cheong *et al.,* 2020, Robinson *et al.,* 2020).

The results show that the use of the low order technique is beneficial due to the significant reduction of acoustic levels. The results demonstrate that the low order charges used can achieve a reduction in peak sound pressure level of between 14 dB and 19 dB and in Sound Exposure Level of between 14 dB and 22 dB compared to high order detonation for charge sizes of 2.5 kg and 5.0 kg.

Post-shot observations and weight measurements suggest that only a modest amount of the surrogate munition charge was consumed during the deflagration shots on the larger surrogates. Although the shell casings were penetrated, there was little visual evidence of significant combustion of the interior explosive filling, and the lack of significant weight loss corroborates this finding.

4.2 DISCUSSION

In this work, a controlled field experiment has been carried out to quantify the reduction in acoustic output level using the ECS low-order charges compared to high-order detonation. The results for the acoustic tests are in accord with the previous study where reductions of around 20 dB were observed in both peak sound pressure level and SEL, equivalent to a factor of 10 in peak sound pressure and a factor of 100 in energy (Robinson *et al.,* 2020). In addition, since UXO sizes can range up to several hundred kilograms, much greater reduction factors are feasible for very large UXO sizes. The results are in accord with the visual impression during the trial where the high-order detonations of a 5 kg shell caused a large airborne plume of water, whereas the deflagration of the same size shell barely disturbed the surface of the water. One difference between the high-order detonations and the deflagration was the presence of the catch-plate for the deflagration. Since the levels measured for the deflagration were very similar to those of the shaped charges alone (with or without placement against a metal plate), it may be concluded that the catch plate did not significantly influence the radiated sound levels (though a small effect cannot be discounted).

The low-order deflagration method offers a substantial reduction in acoustic output over traditional high-order methods. Of note, is the fact that the acoustic output depends on the size of the shaped charge (rather than the size of the UXO itself). This makes the acoustic levels much more predictable compared to high-order detonations where the levels can be unpredictable (Robinson *et al.,* 2022). Compared to high-order methods, deflagration offers the potential for greatly reduced acoustic noise exposure of marine fauna and reduced destruction of the seabed. The shaped charges used in the original study have now been tested in an offshore trial, but this has not yet been undertaken for the ECS technology.

Though the results show that the use of this low order technology would be beneficial acoustically due to the significant reduction of sound level, it is clear from post-shot observations and weight measurements that very little surrogate charge material was combusted during the deflagration shots. This is different to the results from the previous study on deflagration charges where typically more than 50% of the explosive material was consumed by the deflagration (Cheong *et al.,* 2020, Robinson *et al.,* 2020) Although the shaped charge was successfully detonated and penetrated through to the PE14 explosive inside the surrogate shell, it was unclear whether this would have been enough for a UXO to have been successfully disabled by the LX-30 deflagrator from the tests performed here. Therefore, it is not possible to conclude whether a successful deflagration had occurred in terms of the disabling of the target munition. It was also noted that observation of the signal during the surrogate low-order test and the detonation of the shaped charges alone showed little difference in terms of its acoustic spectral content, again suggesting that the deflagration may not have been fully initiated. A video recording of the tests performed by ECS themselves in their own facility had shown what appeared to be a long combustion process after the initial shaped charge is detonated. It is recommended that the further tests be undertaken to confirm the effectiveness of the technology at disabling a UXO (this is beyond the scope of the acoustic study undertaken here).

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6 ANNEX 1: CAD DRAWINGS OF SURROGATE SHELL