JNCC Report 776

Seabed disturbance following high order clearance of unexploded ordnance

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January 2025

ISSN 0963 8091

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This report was produced for JNCC under an external contract, by Simon Cooke and Ross Bardwell of 6 Alpha Associates under contract C22-0287-1691.

This document should be cited as:
Cooke, S.[1] & Bardwell, R.[1] 2025. Seabed disturbance following high order clearance of unexploded ordnance. *JNCC Report 776*. JNCC, Peterborough, ISSN 0963-8091. https://hub.jncc.gov.uk/assets/061e0869-a35a-4bf5-b37f-997883618ee9.

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Acknowledgments:
With thanks to the Offshore Wind Developers who agreed to provide post-disposal reports for the purpose of examination in this study, in confidence.

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Summary

The Joint Nature Conservation Committee, in collaboration with the Institute of Explosive Engineers, has investigated seabed disturbances following unexploded ordnance detonations, to enable the statutory nature conservation bodies to provide informed advice to regulators and developers. The Committee has also engaged *6 Alpha Associates* to provide expert insight into the seabed effects of such unexploded ordnance disposal events in general and their cratering effects in particular.

A predictive model has been proposed to estimate the worst-case effects of seabed cratering, employing existing research literature and experimental data. The model has been compared with real-world, empirical evidence, with *6 Alpha* having analysed many disposal reports and specifically the cratering effects observed post-disposal.

The predictive crater impacts generated by the model has not only been retrospectively corroborated by the empirical evidence but has also demonstrated, that the worst-case scenario, predictive cratering effects have not been exceeded.

The model might, therefore, be employed to inform environmental impact assessments by accounting for a variety of different variables, (e.g. water depths and seabed conditions which influence crater size), and to accurately predict a likely worst-case seabed crater scenario.

Conclusions

From a comparison between theoretical modelling and the empirical evidence, the following conclusions have been drawn:

- In most cases, the estimated modelled crater radii were 25% larger in comparison to the empirical as-measured results. However, it is considered likely that some degree of sediment accretion generated by tidal currents may have occurred post disposal but prior to crater measurements, which could account for this difference.
- It is not expected that the smaller crater radii observed in the empirical data could be attributed to degradation of the explosive fill during the time since it was sited. The explosive fill typically would not degrade in this time and any detonation would be expected to be at the full force and volatility of that when the munition was fresh.
- The modelled crater depth generally showed good correlation to the empirical as-measured results (to within ±10–20%), except for lower NEQ (< 25 kg) disposal events, where the crater depths were observed to be deeper than the maximum estimate generated by the model.
- In all cases reviewed, the ratio of the water depth and charge weight exceeded 2.5. None of the supplied (and complete) Target Disposal Reports (TDRs) indicated a disposal that took place within the bounds of the Critical Ratio (C_R, 1.5 to 1.7). It would be expected that crater dimensions may likely exceed those which have been measured as part of this assessment, if the conditions were such the water depth/charge weight fell within the C_R (e.g. by a detonation occurring at the corresponding depth (or deeper)).
- Nonetheless, no disposal, (up to 250 kg NEQ), showed a measured crater radius exceeding ~5.50 m, nor a depth exceeding ~2.50 m.
- Theoretically, in worst-case and based on extrapolation of the model, extremely large NEQ munitions such as the TMB Mine (NEQ of 720 kg TNT equivalent), could generate a crater of estimated maximum 15.50 m in radius, and 5.20 m in depth, if

the water depth were within the C_R, (nominally, in this case, between 13.50 m and 15.20 m of water). If the mine were in deeper waters, the crater would be expected to be smaller.

- Disposals on mud-based seabed sediments appear to demonstrate cratering with dimensions approximately 50% smaller than that of a similar event on a sand-based seabed, albeit the dataset upon which this observation relies is small. There were insufficient data to determine a similar comparison for a gravel-based seabed.
- Disposals where UXO remains were partially buried tended to generate **deeper***,* but not necessarily **wider** craters, (albeit the dataset upon which this observation relies, is small).
- Employing a bubble curtain does not appear to notably impact the crater size (ditto sample size).

The above conclusions are based on a dataset including munitions up to 250 kg NEQ. Whilst the model presented can be used to estimate craters for munitions with larger NEQs, it was not possible to directly compare estimates presented here to empirical evidence and any estimates may be inaccurate or based on modelling that has not been appropriately adjusted. The available dataset could have been improved had the recorded information from the TDRs been more congruent, consistent and complete from all projects and contractors.

It is noted there is potential for large inconsistencies in the measurement of crater width and depth, as it is inherently difficult to carry out these measurements via a Remotely Operated Vehicle. The process of crater filling from tidal currents will begin immediately following the detonation. The former and latter may reflect in the measurements gathered from post-disposal reports and partly explain inconsistences between modelled and observed events.

Recommendations

Based upon the modelling presented, the observed evidence and *6 Alpha's* professional experience, the following recommendations have been made:

- Provided the water depth is deeper than 11 m, (that is, in excess of the C_R for a 250 kg NEQ munition), and the combined UXO NEQ and donor charges do not exceed 250 kg, the modelled crater radius and depth are likely to give an approximate (±10–25%), upper estimation of the crater radius and depth that may result from a high order detonation, and therefore can be considered a suitable estimation for assessment of the impact on the local seabed.
- Potential craters from any larger combined NEQ detonations could be calculated using the model presented, however, no empirical data are currently available to determine the accuracy of such extrapolation.
- If the position of the UXO (to be disposed of) is in a special or sensitive area, (either ecologically or geologically), such as an SAC, its relocation to a more environmentally benign area should be considered, if it is practicable and safe to do so.
- Safety is paramount when considering the disposal and/or relocation methods, and unacceptable levels of risk (beyond ALARP) must not be introduced whilst seeking to mitigate environmental impacts.
- De-burial operations and the time spent in proximity to UXO increases the exposure to the hazard and the likelihood of premature and unintended detonation, potentially

exposing equipment, vessels, and personnel to unnecessary and unacceptable risks. Therefore, UXO should only be de-buried to the extent required - that is to positively identify it and to determine where a low (or high) order donor charge can be emplaced, to support the render safe procedure. Such de-burial ought not to be continued beyond that necessary for render-safe charge emplacement, nor to mitigate shock wave effects, nor to generate smaller crater sizes.

- Target Investigation Reports, or TIRs, are often repurposed for reporting of disposal activities. By their name, these are often appropriate for investigation activities, but not appropriate for disposal operations. It is recommended that UXO disposal contractors utilise a dedicated TDR reporting template to document disposal-specific information. A standardised 'Target Disposal Report' (TDR) template is recommended for future disposal activities in UK waters, to align the UXO disposal industry reporting and ensure that sufficient information is captured before and after disposal events. 6 Alpha have provided a TDR template for consideration, in Appendix 1.

Contents

1. Project overview

1.1. Background

The Joint Nature Conservation Committee (JNCC) is a statutory adviser to the UK Government and devolved administrations on UK and international nature conservation. The JNCC, in collaboration with the Institute of Explosive Engineers (IExpE), have proposed to investigate seabed disturbance following high order unexploded ordnance (UXO) detonation to allow the JNCC and other Statutory Nature Conservation Bodies (SNCBs) to provide more informed advice to regulators and developers.

Prior to the construction of offshore developments, all sites must be certified as safe and meeting the requirements to reduce the prospective risks associated with UXO to “As Low As Reasonably Practicable” (ALARP). Health and safety requirements mean that once a geophysical survey anomaly that has been designated as potential UXO (pUXO) has been positively identified and verified as confirmed UXO (cUXO) - and in the vast majority of such circumstances cUXO is likely to contain dangerous high explosives – then it must be either relocated and/or disposed of at the earliest opportunity, to avoid it posing a risk to the project as well as to third-party sea users and the general public.

In terms of UXO disposal, a variety of options are available to a developer once UXO has been positively identified however, the most used disposal method has been to employ sympathetic detonation *in situ*. This involves placing relatively large (up to 5 kg) high explosives charge in very close proximity to UXO and initiating them. The resultant shock wave initiates the high explosives contained within UXO (which is referred to as a high-order detonation event).

The scale of potential impacts associated with high-order events may vary depending on the UXO and the amount of high explosives it contains (formally defined as its Net Explosive Quantity (NEQ)), its location and degree of decomposition and sensitivity to shock, as well as its location relative to sensitive receptors.

To date, impact assessments have typically focused on impacts associated with shock waves/noise from high-order detonation events to marine species, however, recent applications to clear UXO inside the Dogger Bank Special Area of Conservation (SAC), have highlighted an important data-gap regarding impacts to the seabed. Much of the data regarding seabed damage currently available for use in such impact assessments has been collected onshore which is not directly comparable to the marine situation. Whilst new low-order methods of clearing UXO are being introduced to the commercial market which should reduce potential impacts to the seabed, high-order clearance will likely have to remain a contingency method, and it will have to be considered in impact assessments.

The precautionary principle requires the worst-case scenario to be considered in impact assessments therefore, a better understanding of associated impacts to the seabed from high-order clearance is expected to help SNCBs provide more informed advice and reduce delays to the consenting process.

6 Alpha Associates (6 Alpha) have been commissioned to provide expert insight into the effect of such UXO disposals on the seabed in the immediate vicinity of the detonation event, to better understand the effects that high order disposal events might have and to better inform regulators, developers and the licensing authorities.

1.2. Aims

This study aims to review existing (publicly available) studies and literature on estimations of seabed crater volume and dimensions relative to UXO NEQ, and to propose a model which could be used to estimate the maximum expected extent of seabed disturbance which might be generated, given a known charge weight, and whether this may be influenced by any combination of the following:

- Water depth
- Type of seabed strata
- Proportion of burial of the munition
- The employment of bubble curtain technology during disposal activities.

This model was directly compared to empirical evidence provided in Target Disposal Reports (TDRs) collated by JNCC for accuracy and appropriateness in estimating future seabed crater sizes generated because of UXO disposal action.

2. Seabed Disturbance: Crater Formation Theory

2.1. Existing Research and Modelling: Land

It is reasonable to assume that munitions (and respectively, their associated donor disposal charges during-low order or high-order render safe procedures) containing higher NEQs will subsequently generate larger shockwaves which propagate with more energy throughout the local sediment and surrounding environment. It is also reasonable to assume that crater width and depth will increase proportionally to the combined NEQ, reflecting the increased energy being released into the subsurface.

This study focusses solely on UXO disposal at sea, and the proposed crater modelling is not influenced by land-based experiments. That said, it is important to consider the inherent differences between crater formation from detonations on land to those in water and, consequently, why land-based models would not be suitably appropriate to be applied to detonations at sea.

There are notably more publications focussing on crater dimensions generated by high explosive events on land than in the maritime domain due to the inherent difficulty with undertaking such experiments at sea, plus disposal events are far more common and easily measured on land.

There are likewise, many more sources for modelling and estimation of the resultant effects for detonations on land. For instance, Merrifield (2000) suggests the relationship between crater radius, r, and mass of the explosive used in kg, M, placed directly on the surface, in the following equation (1):

$$r = kM^{0.33} \quad (1)$$

Where k is the soil coefficient, ranging from very hard soil to very soft soil.

However, for land-based detonations, the craters that are generated are typically steep sided, forming craters much deeper, proportionally, to their respective radius. This means the overall volume of the crater would be greater than would expect from a crater in the marine environment with the same radius.

Considering the focus of this report (i.e. in a maritime setting), and for comparison purposes, a selection of munitions which are widely found in UK waters and their respective crater sizes according to this simple model (and assuming very soft soil conditions), are presented in Table 1.

Table 1: Crater radii using land modelling for a selection of widely found munitions in UK waters (based on Merryfield 2000).

Munition Type	NEQ [kg]	Crater Radius using Merryfield model [m] (Merrifield 2000)
6" Naval Projectile	6	1.3
SC50	25	2.0
SC250	126	3.5
UC-200 Mine	141	3.6
G7 Torpedo	254	4.4
TMB Mine	720	6.1

Other, similar models have been proposed, (e.g. Ambrosini *et al*. 2002), but generally it is agreed that unknown geological characteristics may generate uncertainties and inconsistencies in crater volume estimates to the order of 3 or 4 times, and crater dimensions may vary by as much as 50% when comparing calculated and empirical results on land (Cooper 1976).

Land-based modelling might be interpreted for the marine environment with some additional considerations (which are discussed subsequently, within this report, e.g.Kicinski 2023). These specific, adapted models and their accuracy, however, are not currently supported by empirical evidence therefore, it is not possible to determine with an appropriate degree of accuracy, how the land modelling relates to marine environment.

2.2. Existing Research and Modelling: Marine

In comparison with land modelling, and from 6 Alpha’s own experience, the inherent difference between crater formation from detonations on land and those in the maritime environment, is the effect of “tamping”. Tamping in this context, refers to the force which is imparted by the pressure of the water column (acting under gravity) above the source of the explosive event. In any given depth of water, there is a downward force which is equal to 1,000 kg/m^3 – the mass of the water itself, which effectively increases the resistance of the seabed layer to sediment displacement, and subsequently reduces the likeliness for sediment to distort or eject during high explosive crater formation.

It can therefore generally be expected that craters from underwater detonations form a shallower, but wider crater than those formed on land; however, seabed craters can differ wildly depending on a wide range of criteria, (which are discussed further within this report). It could, however, be generally assumed that as water depths become deeper, the tamping effect is increased and consequently, the seabed has an increased resistance to sediment displacement.

It is therefore not surprising that experimental observations report a rapid decrease in crater size as the water depth increases – although only to a point, and not in a linear fashion. For example, Gorodilov *et al.* (1996) observed that when water depths are comparatively shallow, (nominally, less than 5 m), the process in which seabed craters are formed is predominantly via active sediment ejection, including sometimes through the water surface. Sediment ejection is inherently much more difficult to measure than displacement (i.e. a crater is easier to measure than widely distributed sediment dispersal), therefore confidence in modelled crater sizes is lower when this is the case.

In contrast, as water depths increase, the process by which craters are generated shifts notably toward sediment displacement. This is because the process of sediment ejection must overcome the added downward force of the water, and eventually (with increasing water depth), the ejection process is degraded to the point where sediment cannot as easily move upward, meaning ejection is no longer the predominant crater formation process. This means confidence in modelled crater parameters increases as less of the energy generated by the detonation is lost through ejection, and more energy is directed toward sediment displacement.

Gorodilov has also indicated that in controlled testing underwater on sand, there is an apparent “critical ratio” (C_R) of water depth (D) to charge weight (W) in which the crater radius is expected to be at its maximum. This can be estimated when the following equation (2) is true:

$$\frac{D}{W^{\frac{1}{3}}} = 1.5 \text{ to } 1.7 \qquad (2)$$

Beyond this point, an increased ratio of water depth to charge weight decreases the observed crater dimensions to a point where further increases in water depths have negligible impact on the crater volume. Although a wide variety of factors can influence crater size, experimental results that beyond a ratio between depth to charge weight of 3.0, any decrease in crater size becomes negligible or immeasurable with increased water depth.

By derivation from Gorodilov’s experimental data, the peak crater volume, V, can be estimated relative to the charge weight at approximately 1,600 cm^3 per gram of high explosive NEQ. Considering, nominally, a typical medium scale NEQ of 250 kg, this would expect to generate a crater of maximum volume of displaced sediment of 400 m^3, at a C_R water depth of approximately 10 m.

Cratering generated by marine detonations generally form a shallow dome shape. To take this volume and predict dimensions of a crater, a simple spherical cap model was chosen. The empirical evidence utilised in this study (n-132) indicated that the radius of the crater is typically a factor of three times its depth. Substituting these generalisations into an equation for a volume of a spherical cap (where R is the radius) gives the equation (3):

$$V = \frac{1}{3}\pi\left(\frac{R}{3}\right)^2 * \left(3R - \frac{R}{3}\right) \qquad (3)$$

Which can be re-arranged with the *volume* as the subject and simplified to equation (4):

$$V = \frac{8\pi R^3}{81} \qquad (4)$$

And re-arranged further with *radius* as the subject to equation (5):

$$R = \sqrt[3]{\frac{81V}{8\pi}} \qquad (5)$$

(Where crater depth is also equal to one third of R).

Therefore, in summary, a simple model can be derived whereby:

- The C_R of water depth to charge weight is 1.5 – 1.7. At this depth, the volume of a crater formed relative to charge weight is approximately 1,600 cm^3/g.

- Water depths shallower or deeper than that of C_R will mitigate the volume of crater formation, equalising at a crater volume relative to charge weight of approximately 500 cm^3/g.

Marine license applications for UXO clearance typically model a range of potential UXO charge weights, with the worst-case charge size typically assessed being a 700 kg NEQ UXO. The minimum and maximum water depths at which a critical ratio with explosive weight is achieved (i.e. C_R 1.5 or 1.7 respectively) for detonations of NEQs up to 700 kg is presented in Figure 1. Between these, crater volume is expected to be at its maximum.

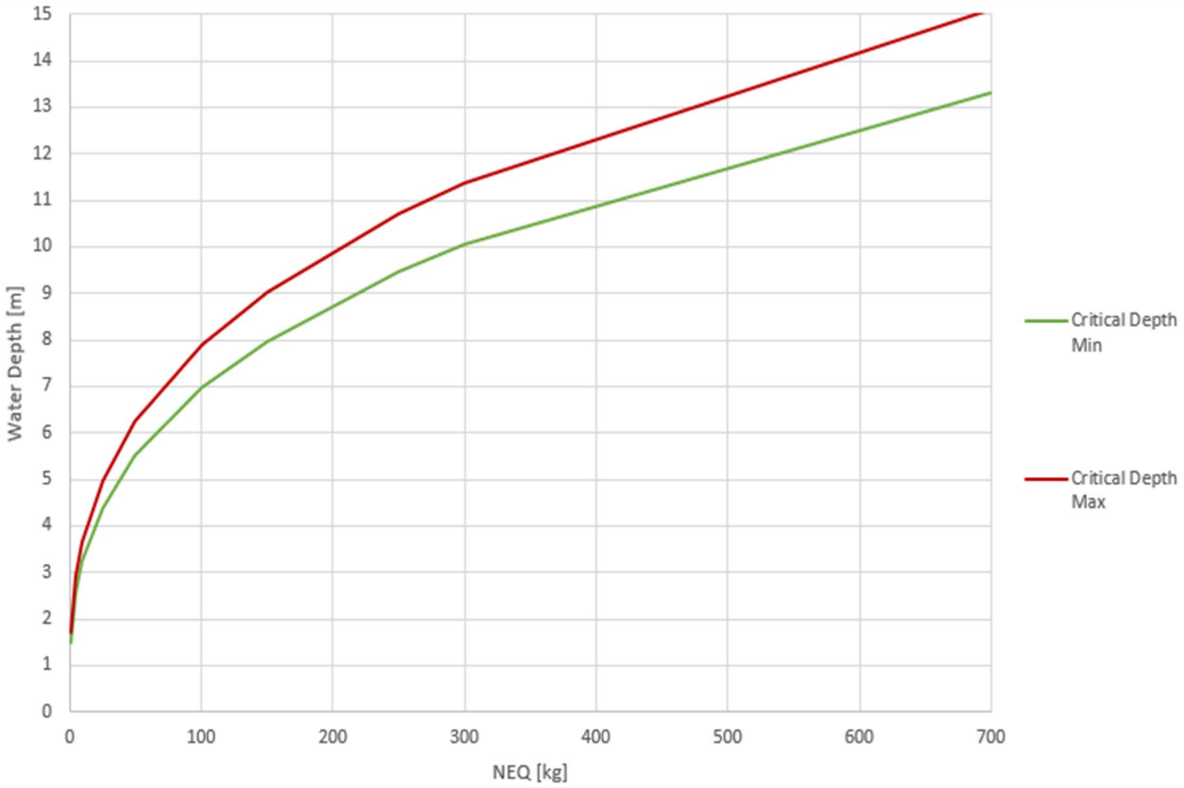

Figure 1: Illustration of the critical ratio (CR), and its relationship between water depth and high explosive volume (NEQ; based on Gorodilov *et al.* 1996). The lower green line represents the minimum critical depth and the upper red line the maximum. Detonations occuring in conditions which fall between these lines will be the biggest.

Typically, the model predicts that water depths deeper than ~15 m should mitigate crater volumes for even the largest expected NEQ munition detonations. Crater sizes in water depths shallower than the C_R are less predictable but are still not observed to be higher than that of those observed within the C_R from Gorodilov's experimental results.

Considering the above, a breakdown of the C_R water depths and modelled expected maximum crater characteristic, (that is, utilising volumetric estimates of 1,600 cm^3/g of NE, and depth is one third of the radius) for typical munitions found in UK waters are summarised in Table 2 below.

Notwithstanding Table 2, considering that deeper water disposals are more likely on most offshore wind farm sites, (except perhaps, the nearshore cable landing elements), re-evaluated model considering lower thresholds outside of C_R utilising a volumetric estimate of 500 cm^3/g of NEQ, are summarised in Table 3.

Table 2: Expected maximum size and crater characteristics for typical munitions if detonated at critical water depth to charge ratio (Gorodilov *et al*. 1996).

Munition Type	NEQ [kg]	Critical Water Depth [m]	Modelled Crater Volume [m^3]	Modelled Crater Radius [m]	Modelled Crater Depth [m]
6" Naval Projectile	6	2.70 – 3.10	9.60	3.10	1.00
SC50	25	4.40 – 5.00	40.00	5.10	1.70
SC250	126	7.10 – 8.50	201.60	8.70	2.90
UC-200 Mine	141	7.10 – 8.80	225.60	9.00	3.00
G7 Torpedo	254	9.50 – 10.80	406.40	10.90	3.60
TMB Mine	720	13.50 – 15.20	1,152.00	15.50	5.20

Table 3: Expected maximum size and crater characteristics for typical munitions detonated at water depths outside of the critical water depth to charge ratio (Gorodilov *et al*. 1996).

Munition Type	NEQ [kg]	Modelled Crater Volume [m^3]	Modelled Crater Radius [m]	Modelled Crater Depth [m]
6" Naval Projectile	6	3.00	2.10	0.70
SC50	25	12.50	3.40	1.10
SC250	126	63.00	5.90	2.00
UC-200 Mine	141	70.50	6.10	2.00
G7 Torpedo	254	127.00	7.40	2.50
TMB Mine	720	360.00	10.50	3.50

The modelled crater radii outside of the critical water depth range is approximately two-thirds of that inside of the critical water depth range, for each of the typical munitions. It is considered this model is most appropriate based on the experimental data on which it relies upon, and its focus on the fundamental forces involved when considering marine detonations as compared with land scenarios.

3. Review of Disposal Events

3.1. Empirical Evidence

Prior to this assessment, the JNCC reached out to the Institute of Explosive Engineers and offshore wind farm (OWF) developers to acquire crater data from UXO disposal activities that had taken place within UK waters. A collection of TDRs, (which are often inaccurately internally referred to as 'TIRs'), were collated from eight large scale OWF projects, that included more than 300 disposal events of varying natures and scales.

6 Alpha reviewed these TDRs, analysing their content based on the following quality control measures:

- The accuracy of the as-reported classifications of UXO and whether coherent with the supplied underwater imagery and 6 Alpha's in-house EOD knowledge and experience.
- Ascertained that the minimum required information on crater size was provided, and where it was, that it was accurate and consistent with any underwater imagery/survey data provided as part of that TDR.
- Identify any inconsistencies which may question the as-reported results to an extent that the TDR may be rejected based on lack of confidence.
- Update any obvious typos, misclassifications, or inaccuracies which, in 6 Alpha's professional opinion and experience, could be easily rectified with confidence, to then allow said TDR to be included in the assessment.

The following data was extracted from the TDRs that met the quality control criteria and collated in a database:

- UXO type and NEQ of main charge weight and donor charge
- Low or high order detonation method
- Crater diameter and depth
- Water depth
- Sediment type
- Use of bubble curtain.
- Any remarks which might otherwise impact the interpretation of the data therein.

The quality control exercise highlighted inconsistencies in the level of detail included in the TDRs across the UXO risk management industry, including inputs from UXO consultants and disposal contractors. There were neither congruency nor consistency of reporting between the TDRs that critically for this project, did not often contain usable information concerning seabed post-disposal conditions, and therefore a great number of the TDRs were considered unsuitable.

In addition, a smaller proportion of the remaining TDRs contained some data, but did not contain sufficient information on the nature of the UXO being rendered safe, nor its NEQ. Subsequently it was not possible to estimate the expected quantity of high explosive fill of either the UXO or the donor charge employed to render it safe. These TDRs were removed from the analysis, as were others that were similarly anomalous (e.g. the post-disposal measurements appeared either inaccurate or incorrect).

Notwithstanding the necessary TDR quality filtering, 132 individual disposal events and their respective TDRs were suitably and sufficiently detailed to inform the empirical analysis associated with this assessment. The munitions that had been disposed of within this filtered dataset ranged between 0.1 kg and 250 kg NEQ of high explosives.

3.2. Crater Radius and Depth Analysis

For the purposes of data comparison, the combined NEQ of the munition and donor charge were used to calculate the “charge weight” value. Furthermore, because it was not possible to discern from the TDRs if either a full or partial deflagration event had occurred, it was assumed that all craters were generated by a high-order detonation event.

Using the model described previously, crater radii values for NEQs up to 300 kg were calculated and plotted as an upper estimate at C_R, (i.e. where $V = 1,600\ cm^3/g$) and a lower estimate in deeper water depths (i.e. where $V = 500\ cm^3/g$). The measured crater radii were plotted on the same axes for the disposal events and are presented in Figure 2. The same process was completed for the measured crater depths, and the results are presented in Figure 3.

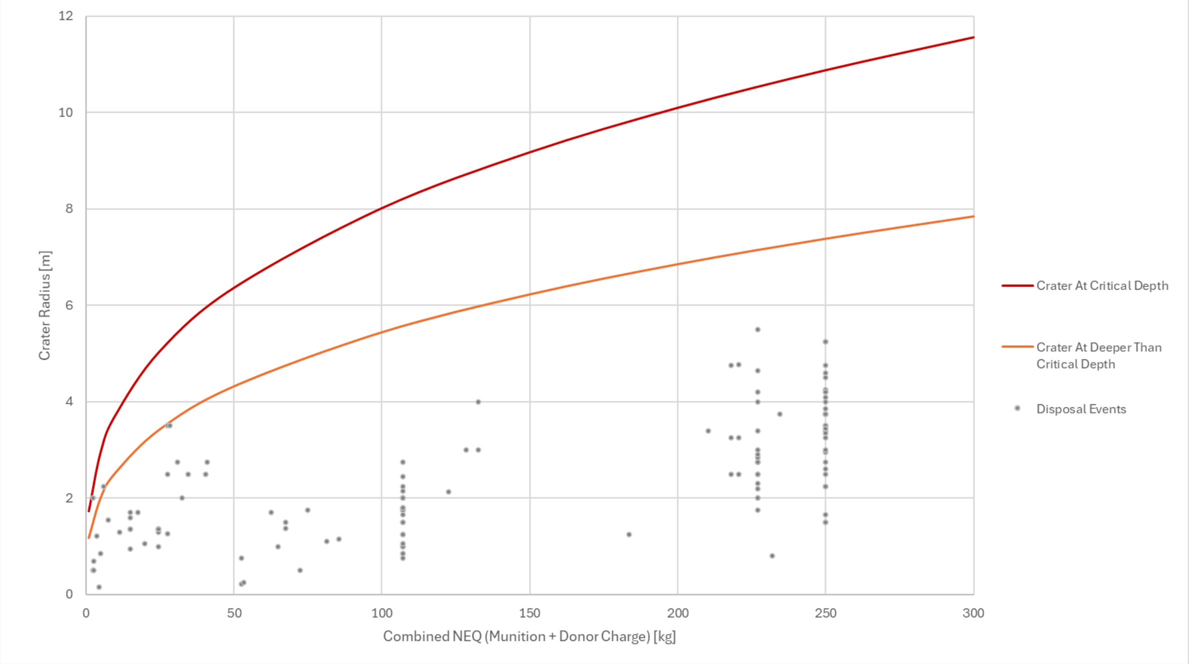

Figure 2: Modelled crater radii for detonations at critical depth (CR, upper red line) and in waters deeper than the critical depth (lower orange line), overlain with real-world disposal event measurements from TDRs (dots). Virtually all real-world measurements are below the modelled cater radii for the respective conditions.

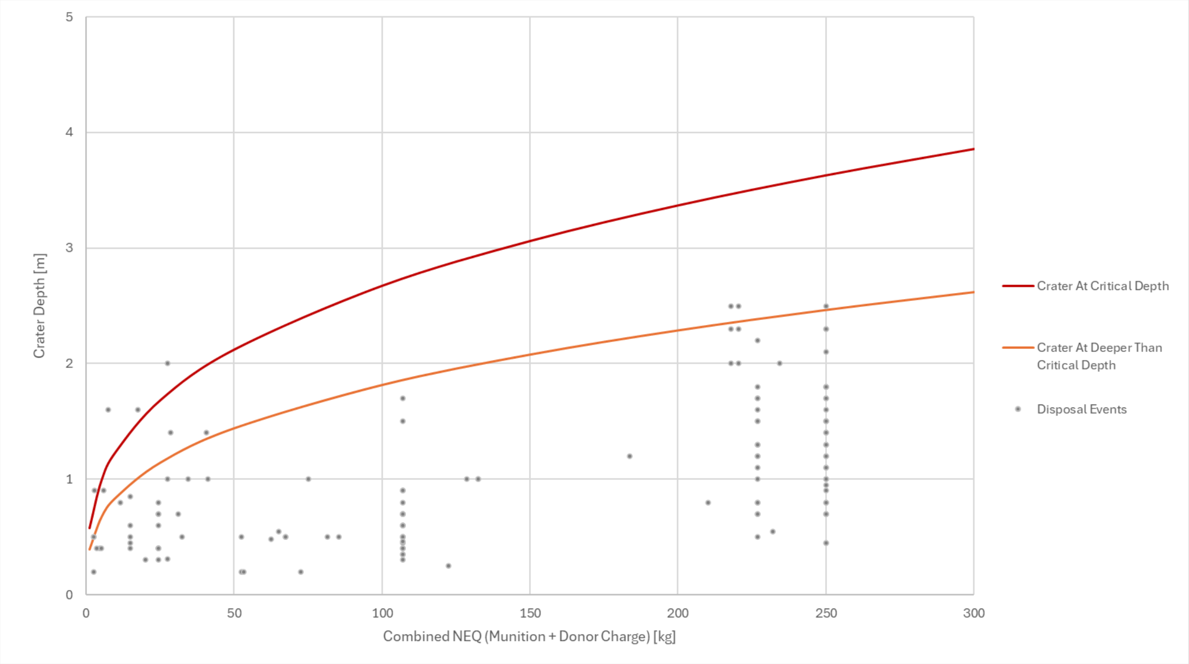

Figure 3: Modelled crater depth for detonations at critical depth (CR, upper red line) and deeper than critical depth (lower orange line), overlain with real-world disposal event measurements from TDRs (dots). The majority of real-world measurements are below the modelled cater depth for the respective conditions.

In Figures 2 and 3, it is apparent that there is a wide distribution of crater characteristics for events generated by the apparent same UXO/NEQ however, most of them fall below the upper estimates generated by the model. Additionally:

- There was no evidence within this dataset to indicate that a crater from a disposal event up to 250 kg NEQ would exceed approximately ~5.5 m in radius, nor ~2.5 m in depth.
- Modelled crater depths tended to more closely match to the empirical crater depth results than modelled/actual crater radii. Occasionally, the empirical results for radii were more than the modelled “worst case” for lower NEQ items (that is, approximately 25 kg and below).
- There is a wide spread of crater measurements across all UXO NEQs, suggesting that there are significantly more factors involved in deriving these estimates, including but not limited to: the subsurface conditions, strata type, depth of surficial sediment and proportion of the UXO that is buried below the seabed at the point of its disposal.

3.3. Seabed Strata

Of the 132 disposal events considered, 115 were indicated as being on a seabed categorised as predominantly sand, with 12 events having taken place on mud, and the remaining five on gravel. Given the relatively small dataset for mud and gravel, any conclusions gathered from the empirical data is de facto based on the small statistical sample of specific events. Nonetheless, the results for crater radius and depths were plotted and categorised according to their seabed types, presented in Figures 4 and 5 respectively.

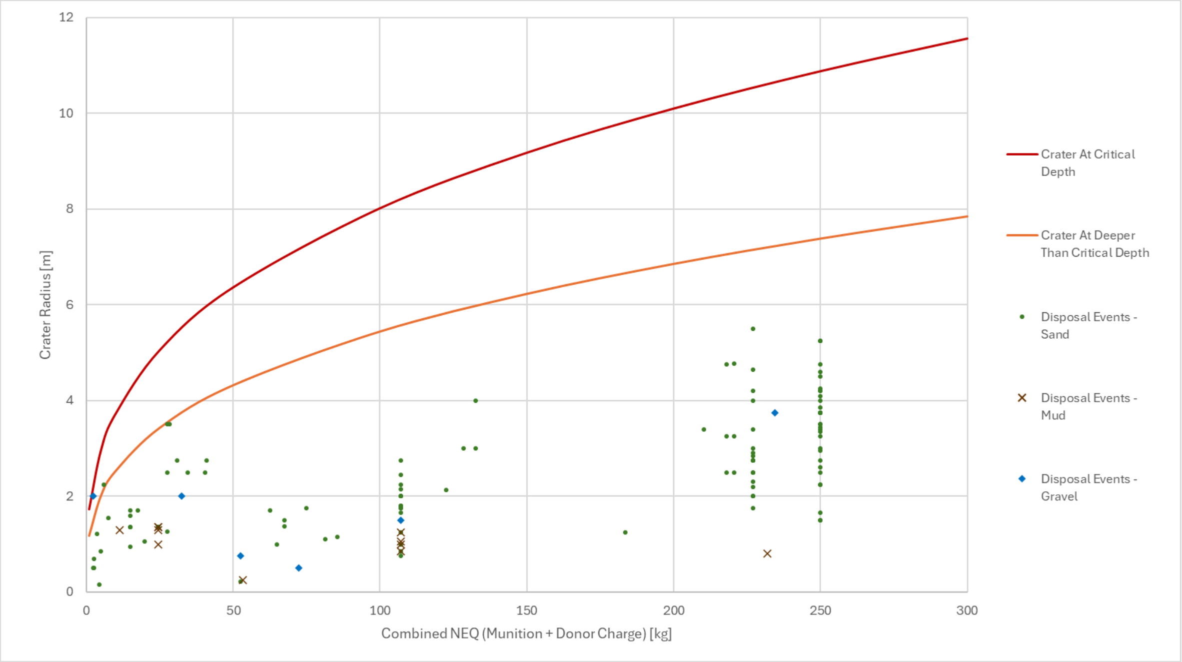

Figure 4: Modelled crater radii for detonations at critical depth (CR, upper red line) and deeper than critical depths (lower orange line), overlain with real-world disposal event measurements separated by sediment type (green dots = sand; brown crosses = mud, blue diamonds = gravel).

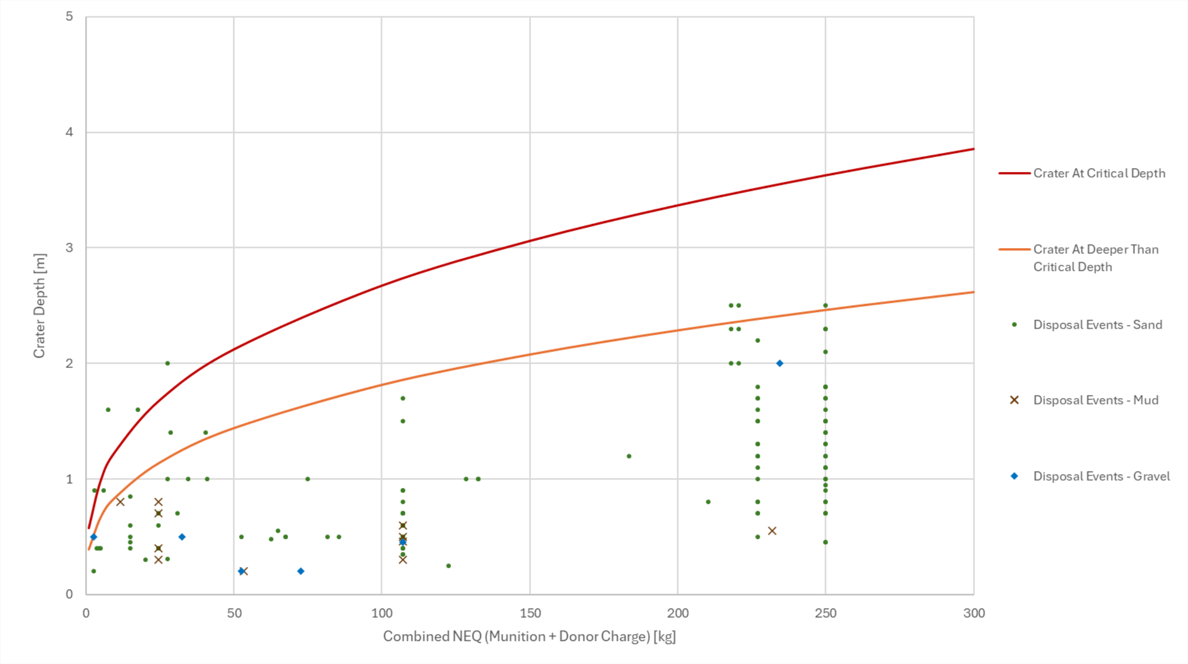

Figure 5: Modelled crater depth for detonations at critical depth (CR, upper red line) and deeper than critical depth (lower orange line), overlain with real-world disposal event measurements separated by sediment type (green dots = sand; brown crosses = mud, blue diamonds = gravel).

Despite the reservations with using a small sample size, the results tend to place detonations on mud-based seabed in the lower half of typical crater radius and depth categories. It is reasonable to theorise that the muddy sediment may not be as readily ejected from the crater due to its relative glutinous state, and/or this type of seabed may behave more elastically than compared with say, a more sand-based seabed. It might, therefore, be suggested that detonations on a seabed that is primarily mud-based could generate smaller craters, possibly in the order of 50% smaller both in radius and depth, but further empirical evidence would be required to confirm such a provisional conclusion.

In general, there is little correlation from the small dataset of gravel seabed detonations, and in 6 Alpha's view, any specific conclusion cannot be reliably drawn. As a working hypothesis therefore, crater radius and depth in gravel are equally likely to be of the same magnitude as those generated in sandy seabed conditions.

In any case, the effect that the seabed particle size and surrounding strata has on crater characteristics is difficult to determine due to the complex categorisation of marine sediments, blurring the line between sand, gravel and mud (Sakai *et al.* 1971).

3.4. Extent of Burial

There are many factors which contribute to burial of munitions. Water depth is one of them, as well as the weight of a munition, but also seabed currents, and any mobility/subsequent burial post-conflict - therefore it is difficult to determine with confidence if smaller or larger munitions are less or more likely to be buried when found. When UXO are investigated and are discovered subsurface, they are usually excavated only to the extent that they can be identified. Subsequently, they might be further exposed but only to the extent that the disposal charge can be emplaced. Therefore, UXO may remain partially buried throughout the verification and disposal processes.

Of the 132 disposal events, 73 had sufficient information to estimate the percentage of burial in the seabed at the time of disposal. Considering the differences in which disposal events have been categorised and reported, the results have been separated into those which were on the seabed surface (categorised as less than 10% burial, n = 50), and those which were partially buried (categorised as greater than 10% burial, n = 23).

Unfortunately, those results which were categorised as on the seabed surface were exclusively of 200 kg NEQ and above, diminishing the prospective usefulness of the comparison. Nonetheless, the measured crater radii and depths for the 73 disposal events have been plotted and are provided graphically at Figures 6 and 7.

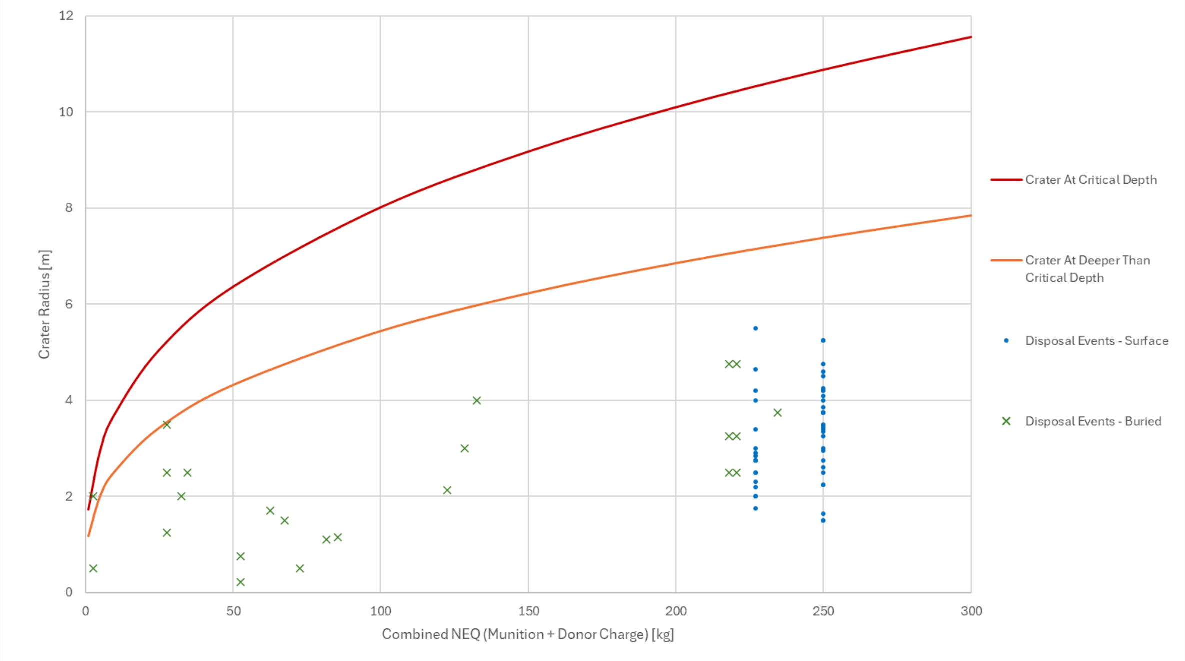

Figure 6: Modelled crater radii for detonations at critical depth (CR, upper red line) and deeper than critical depth (lower orange line), overlain with real-world disposal event measurements separated by burial extent (detonations on the seabed surface = blue dots, buried detonations = green crosses).

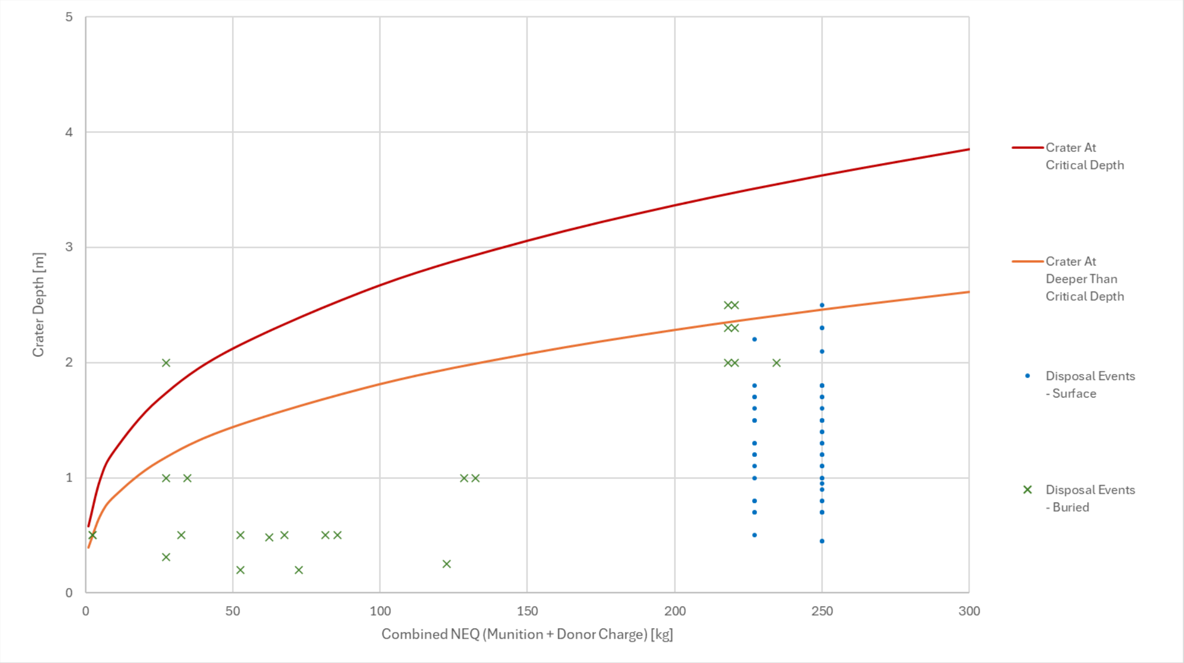

Figure 7: Modelled crater depth for detonations at critical depth (CR, upper red line) and deeper than critical depth (lower orange line), overlain with real-world disposal event measurements separated by burial extent (detonations on the seabed surface = blue dots, buried detonations = green crosses).

Considering the reservations that all ‘at seabed’ disposals were more than 200 kg NEQ, one conclusion that might be drawn is that UXO detonations which remain partially buried (that is, not fully excavated, de-buried or repositioned to an undisturbed seabed elsewhere) generate a deeper crater, although not necessarily one that is wider. There is notable clustering of events of detonations for NEQs above 200 kg, where the buried disposal events make up a good proportion of the deepest craters.

It is reasonable to theorise therefore, that if a UXO is partially buried then much of the resultant detonation shockwave is likely to be focussed into the seabed surrounding and below it. In such circumstances the crater depth will generally be expected to be deeper.

A provisional conclusion that might therefore be drawn, is that to reduce cratering, buried UXO might be either de-buried (to an extent that is both safe and reasonably practicable to perform), or otherwise relocated (ditto) to an environment where burial is unlikely to take place in the short term (i.e. not before the render safe procedure is to be undertaken). The pursuit of such a tactic, however, must not be undertaken at the expense or compromise of safety.

3.5. Bubble Curtains

To mitigate the environmental impact of shockwave effects through the water column, and reduce deleterious effects on marine wildlife, bubble curtains are sometimes employed in advance of a UXO render safe procedure. Bubble curtains surround the UXO, and their effect disrupts the water column reducing (theoretically), the propagation efficiency of the underwater shockwave reducing both its intensity and thus its subsequent destructive effect on the surrounding environment.

Whilst bubble curtains are not specifically employed with the intention of diminishing crater formation, for completeness of analysis the potential effects of bubble curtains on resultant craters has been considered as part of this assessment. Of the 132 TDRs that contributed to the study database, 18 of them employed bubble curtains at the time of the detonation event. The results of these events are highlighted amongst the full dataset in Figures 8 and 9.

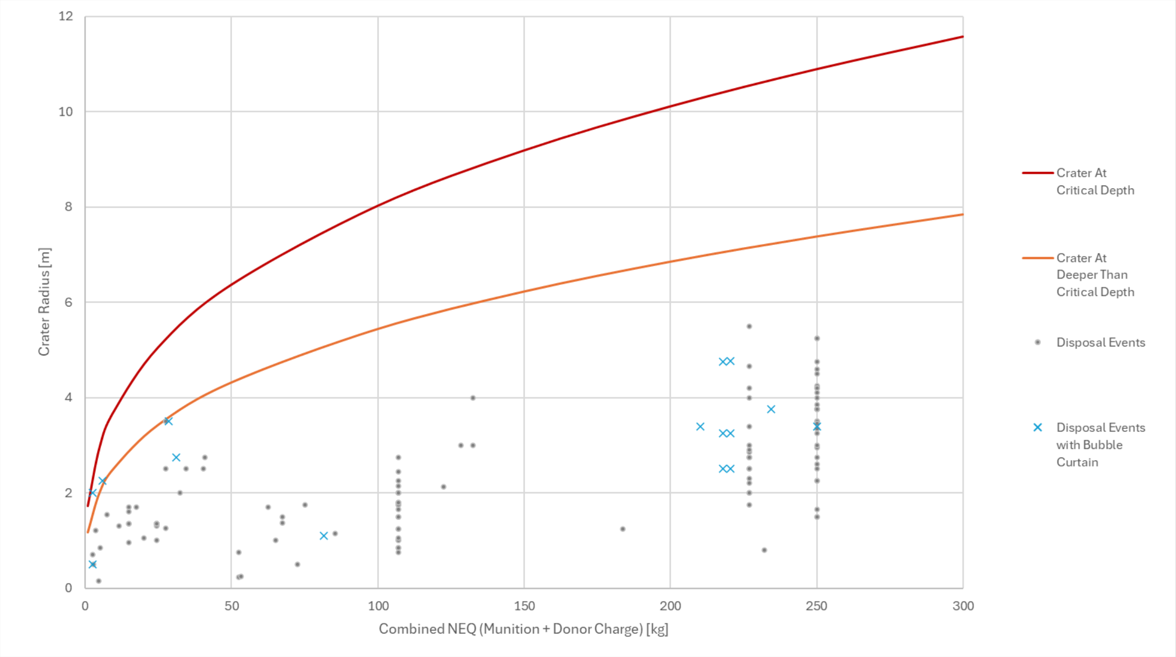

Figure 8: Modelled crater radii for detonations at critical depth (CR, upper red line) and deeper than critical depth (lower orange line), overlain with real world disposal event measurements with (blue crosses) and without bubble curtains (grey dots). Data suggests no difference with the presence of a bubble curtain.

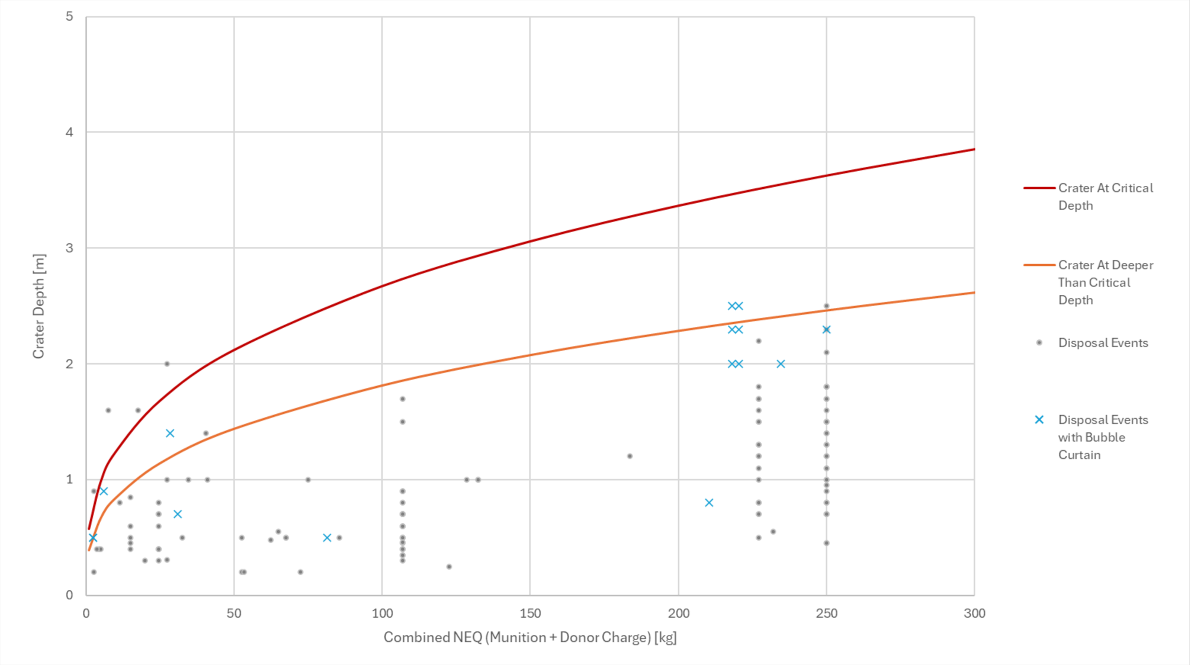

Figure 9: Modelled crater depth for detonations at critical depth (CR, upper red line) and deeper than critical depth (lower orange line), overlain with real-world disposal event measurements, with (blue crosses) and without bubble curtains (grey dots). Data suggests no difference with the presence of a bubble curtain.

Generally, there is no apparent correlation or indeed difference between crater dimensions generated with or without the employment of a bubble curtain. In fact, some of the largest relative crater sizes have been generated when a bubble curtain has been employed however, that is not to suggest that there is any evidence that the systems amplify the cratering effect in any way.

4. Conclusions

The following conclusions have been drawn from the analysis of a dataset consisting of 132 disposal events, and a comparison between theoretical modelling and the empirical evidence. Not all samples in the dataset were fully employed for all phases of analysis because of either inconsistency and/or the unavailability of the required UXO NEQ or *inter alia* crater measurements. 6 Alpha have, in some cases, used their best professional judgement to adjust values they believe may have been entered in error.

- In most cases, the estimated modelled crater radii were 25% larger in comparison to the empirical as-measured craters. However, it is considered likely that some degree of sediment accretion generated by tidal currents may have occurred post disposal but prior to crater measurements, which could account for this difference.
- It is not expected that the smaller crater radii observed in the empirical data could be attributed to degradation of the explosive fill during the time since it was sited. The explosive fill typically would not degrade in this time (e.g. Novik 2022) and any detonation would be expected to be at the full force and volatility of that when the munition was fresh.
- In contrast, the modelled crater depth generally showed good correlation to the empirical as measured results (to within ±10–20%, except on lower NEQ (less than 25 kg) disposal events, where the crater depths were observed to be deeper than the maximum estimate generated by the model.
- In all cases, the ratio of the water depth and charge weight were more than 2.5. None of the analysed TDRs indicated a disposal that took place within the bounds of the C_R, (1.5 to 1.7).
- None of the disposals examined, (up to 250 kg NEQ), showed a measured crater radius exceeding ~5.50 m, nor a depth exceeding ~2.50 m.
- Theoretically, in worst-case and based on extrapolation of the model, extremely large NEQ munitions such as the TMB Mine (NEQ of 720 kg TNT equivalent), could generate a crater of estimated maximum 15.50 m in radius, and 5.20 m in depth, if the water depth was that to be within the C_R, (nominally, in this case, between 13.50 m and 15.20 m of water). If the mine were in deeper waters, the crater would be expected to be smaller and shallower.
- Disposals on mud-based seabed conditions appear to demonstrate cratering with dimensions approximately 50% smaller than that of a similar event on a sand-based seabed, albeit the dataset upon which this observation relies is small. There were insufficient data to determine a similar comparison for a gravel-based seabed.
- Disposals where UXO remains partially buried tend to generate **deeper***,* but not necessarily **wider** craters, (albeit the dataset upon which this observation relies, is small).
- Employing a bubble curtain does not appear to notably impact the crater size (ditto sample size).
- The assessment of the empirical evidence could be improved had the recorded information from the TDRs been more congruent, consistent and complete from all projects and contractors.

The above conclusions derived are based on a dataset including munitions up to 250 kg NEQ. Whilst the model presented can be used to estimate craters for munitions with larger NEQs, it was not possible to directly compare estimates presented here to empirical evidence and any estimates may be inaccurate or based on modelling that has not been appropriately adjusted. The available dataset could have been improved had the recorded information from the TDRs been more congruent, consistent and complete from all projects and contractors.

It is noted there is potential for large inconsistencies in the measurement of crater width and depth, as it is inherently difficult to carry out these measurements via a Remotely Operated Vehicle. The process of crater filling from tidal currents will begin immediately following the detonation. The former and latter may reflect in the measurements gathered from post-disposal reports and partly explain inconsistences between modelled and observed events.

Based on the proportion of TDRs that were insufficiently detailed for the purposes of this assessment, post disposal TDRs across the UXO industry are unhelpful in that they do not readily enable either benchmarking, congruent assessment, or further informed study. Subsequently, 6 Alpha recommended that a standardized TDR template should be considered and distributed to UXO disposal contractors, developers and regulators, ensuring that post disposal information is captured in a consistent fashion and format, so that it may in future better inform further updates concerning seabed cratering effects as well as those studies related to the environmental effects of UXO disposal activities. We have provided an example TDR template at Appendix 1.

5. Recommendations

Based upon the modelling, the observed evidence and 6 Alpha's professional experience, the following recommendations have been made:

- Provided the water depth is deeper of 11 metres, (that is, in excess of the C_R considering a 250 kg NEQ munition), and that the combined UXO NEQ and donor charges do not exceed 250 kg, the modelled crater radius and depth from the model are likely to give an approximate (±10–25%), upper estimation of the crater radius and depth that may result from a high order detonation, and therefore can be considered a suitable estimation for assessment of the impact on the local seabed.
- Potential craters from any larger combined NEQ detonations could be calculated using the model, however, collection of further empirical evidence is required for comparison to determine the accuracy of such extrapolation.
- If the position of the UXO (to be disposed of) is in a special or sensitive area, (either ecologically or geologically), such as an SAC, its relocation to a more environmentally benign area should be considered, if it is practicable and safe to do so.
- Safety is paramount when considering the disposal and/or relocation methods, and unacceptable levels of risk (beyond ALARP) must not be introduced whilst seeking to mitigate environmental impacts.
- De-burial operations and the time spent in proximity to UXO increases the exposure to the hazard and the likelihood of premature and unintended detonation, potentially exposing equipment, vessels and personnel to unnecessary and unacceptable risks. Therefore, UXO should only be de-buried to the extent required - that is to positively identify it and to determine where a low (or high) order donor charge can be emplaced, to support the render safe procedure. Such de-burial ought not to be continued beyond that necessary for render-safe charge emplacement, nor to mitigate shock wave effects, nor to generate smaller crater sizes.
- Target Investigation Reports, or TIRs, are often repurposed for reporting of disposal activities. By their name, these are often appropriate for *investigation activities,* but *not* appropriate for disposal operations. It is recommended that UXO disposal contractors utilise a dedicated TDR reporting template to document disposal-specific information. A standardised 'Target Disposal Report' (TDR) template is recommended for future disposal activities in *UK* waters, to align the UXO disposal industry reporting and ensure that sufficient information is captured before and after disposal events. 6 Alpha have provided a TDR template for consideration, at Appendix 1.

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Appendix 1: Target Disposal Report Form

Project Name:		Project Number	
TIR Ref No		Date	
UXO / Survey		Vessel	

Target Investigation As Found Position	Target ID		RPL Geo Reference	
	KP (0.0)		Positional Reference	
	Easting		Northing	
	Water Depth		Anomaly Data Values	
	Size (cm) L x W x H	L	W	H

Date / Time UTC	Start		End	

Conditions	Wave.Hs.(m)	TW Visibility (m)	Seabed Sediment Type	Current (kn)

Equipment Used	Insert Spread Type

Methodology	

Investigation Results	UXO Y/N		Depth of Burial (m) Target Found	
	Target Description		Depth of Burial (m) Extent	
	Water Depth (m)		Estimated Mass Kg (AUW)	
	Approx. Target Size (cm) L x W x H	L	W	H

UXO	Type		Period	
	Sub Group (1)		Fuse	
	Sub Group (2)		Condition Status	
			Hazard / Fill	
	Origin		NEQ Kg	

Disposal Methodology	High Order		NEQ Kg	
	Low Order		NEQ Kg	
	Relocation / Other			

Marine Mammal Mitigation Protocol	MMO Deployed			
	ADD Deployed		Soft Start 001	
	PAMS Deployed		Soft Start 002	
	Bubble Curtain Deployed		Soft Start 003	

NOTAM Issued	Date		Reference Number	

“All Ships” Radio Broadcast	Date		Time	

Time of Disposal Activity - 001	Date		Time	
Time of Disposal Activity - 002	Date		Time	

Post Disposal Position (if different from as found position)	Easting		Northing	

Post Disposal Crater Data (m)	L	W	D

Supplied Survey GIS Target Images

Pre-Disposal – As Found Original Image – ROV – Diver Camera or Aris Image

Post-Disposal Image – ROV – Diver Camera or Aris Image

MBES (IAW POP) Pre-Disposal

MBES (IAW POP) Post-Disposal

EOD Comments	Insert Comments

Client Rep Comments	Insert Comments

Signature Block			
Designation	Name	Signature	Date

Appendix 2: Acronyms and Abbreviations

Acronym	Description
ALARP	As Low As Reasonably Practicable
CIRIA	Construction Industry Research and Information Association
C_R	Critical Ratio
cUXO	Confirmed UXO
g	Gram
IExpE	Institute of Explosive Engineers
JNCC	Joint Nature and Conservation Committee
kg	Kilogram
km	Kilometre
m	Metre
NEQ	Net Explosive Quantity
pUXO	Potential UXO
SAC	Special Area of Conservation
SNCB	Statutory Nature Conservation Bodies
TDR	Target Disposal Report
TIR	Target Investigation Report
TNT	Trinitrotoluene
UK	United Kingdom
UXO	Unexploded Ordnance