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A User Interface for Rapid Underwater Explosion Threat Assessment

Mark Riley

Defence R&D Canada – Atlantic

Technical Memorandum

DRDC Atlantic TM 2011-131

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Abstract

This report describes a new software tool, UNDEX_Zones, which has been developed for rapid, simplified assessment of damage to surface ships from underwater explosion (UNDEX) threats. Damage is determined using shock severity, as measured by the shock factor (SF), which has been found to be correlated with historical data on the level of damage sustained by a vessel. UNDEX_Zones graphically displays damage zones for a range of charge sizes and charge depths for a given explosive type and ship draft. The damage zones include no damage, varying levels of non-lethal disabling damage, and lethal damage. The present document provides the background theories that were used in the development as well as the functionality and operating procedures of UNDEX_Zones.

Résumé

Le présent rapport décrit un nouvel outil logiciel, nommé UNDEX_Zones, qui a été conçu pour effectuer une évaluation rapide et simplifiée des dommages sur un navire de surface causés par des explosions sous-marines (UNDEX). L'importance des dommages est déterminée par la gravité du choc, qui est mesurée par le facteur de choc, en corrélation avec les données historiques par rapport au niveau de dommages subis par un navire. Le logiciel UNDEX_Zones affiche les zones de dommages afin d'établir la taille et la profondeur des charges pour un type d'explosif et un tirant d'eau de navire spécifiques. Les zones de dommages comprennent la zone sans dommages, les zones de divers niveaux de dommages majeurs non létaux et les dommages létaux. Le présent document fournit les connaissances théoriques qui ont été utilisées pour la conception, ainsi que les procédures de fonctionnalité et de fonctionnement du logiciel UNDEX_Zones.

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Executive summary

A User Interface for Rapid Underwater Explosion Threat Assessment

Mark Riley; DRDC Atlantic TM 2011-131; Defence R&D Canada – Atlantic; June 2011.

Introduction: Ship vulnerability to underwater explosion loading has been an area of ongoing research at DRDC Atlantic for the past decade. Most studies have been focused on experimental and numerical modelling capabilities. Due to the extensive computational cost of running numerical analyses of UNDEX, a user interface, UNDEX_Zones, has been developed to perform rapid assessments of damage levels on a vessel due to an UNDEX event. This tool is based on shock factors, which have historically been used to estimate the degree of damage to a surface ship from underwater explosions. It graphically displays zones based on the anticipated outcome including an Undamaged zone, a Damaged zone, and a Kill zone, where the shock factor limits corresponding to these zones, which are defined by the user.

Results: This report outlines the functionality and the user operations of UNDEX_Zones. The software was designed to be user friendly while allowing the user to control the key input parameters. The inputs that can be defined by the user include the limiting shock factors which separate the different zones, the type of charge material, the minimum and maximum charge sizes used to define the limits for the graphical display, and the draft of the ship. A charge library was created based on data available in the open literature. This library is used in UNDEX_Zones to define the charge types available to the user, and the library can be modified if the required charge type is not included.

Significance: Currently there are few analysis tools available for predicting the damage to a full scale ship due to underwater explosions. The programs that do exist require a significant amount of training to use, and a significant amount of time to perform an analysis. UNDEX_Zones can be used with minimal training and takes only seconds to execute. Although a more detailed numerical study could indicate the full extent of the damage due to an UNDEX event, UNDEX_Zones provides a method to quickly estimate the extent of damage.

Future plans: The current application is developed for under keel explosions only. Future plans are to enhance UNDEX_Zones to allow for off centerline detonations as well as an input for various ship hull geometries.

Sommaire

A User Interface for Rapid Underwater Explosion Threat Assessment

Mark Riley; DRDC Atlantic TM 2011-131; R & D pour la défense Canada – Atlantique; juin 2011.

Introduction : La vulnérabilité des navires aux explosions sous-marines est un secteur de recherche continue depuis les dix dernières années à RDDC Atlantique. La plupart des études portaient principalement sur les capacités de modélisation expérimentale et numérique. En raison des coûts de calcul élevés nécessaires pour effectuer des analyses numériques sur les explosions sous-marines, une interface utilisateur, nommée UNDEX_Zones, a été mise au point dans le but d’effectuer des évaluations rapides de l’importance des dommages sur un navire causés par des explosions sous-marines. Cet outil est fondé sur les facteurs de choc qui, par le passé, ont été utilisés pour estimer le degré de dommages subis par un navire de surface en raison d’explosions sous-marines. Le logiciel UNDEX_Zones affiche des zones en fonction des conséquences prévues des explosions, y compris une zone sans dommages, une zone de dommages et une zone létale, où le facteur de choc apporte des limites en fonction de ces zones, qui sont définies par l’utilisateur.

Résultats : Le présent rapport décrit la fonctionnalité du logiciel UNDEX_Zones et les opérations que peut effectuer l’utilisateur. Ce logiciel a été conçu pour être très facile d’utilisation et pour permettre à l’utilisateur de gérer les paramètres de saisie clés. Les paramètres qui peuvent être définis par l’utilisateur comprennent les facteurs de choc limitatifs qui séparent les différentes zones, le type de matériau des charges, la taille minimale et maximale des charges utilisées pour définir les limites de l’affichage graphique, ainsi que le tirant d’eau du navire. Une bibliothèque sur les charges a été créée à l’aide des données disponibles dans les publications libres d’accès. Cette bibliothèque est utilisée dans le logiciel UNDEX_Zones pour définir les types de charges à la disposition de l’utilisateur et elle peut être modifiée si le type de charge nécessaire n’est pas compris.

Importance : Actuellement, un certain nombre d’outils d’analyse sont disponibles pour prédire les dommages sur un navire à pleine échelle causés par des explosions sous-marines. Les programmes qui existent nécessitent une quantité importante de formation pour les utiliser, ainsi qu’un temps considérable pour effectuer une analyse. On peut utiliser le logiciel UNDEX_Zones même si on ne possède qu’une formation minimale, et il ne faut que quelques secondes pour l’exécuter. Même si une étude numérique plus détaillée pourrait indiquer l’étendue complète des dommages causés par des explosions sous-marines, le logiciel UNDEX_Zones fournit une méthode servant à estimer rapidement l’étendue des dommages.

Perspectives : L’application actuelle est conçue uniquement pour des explosions sous la quille. Dans l’avenir, nous prévoyons améliorer le logiciel UNDEX_Zones dans le but d’inclure également des données de détonations hors de l’axe pour diverses géométries de coque de navire.

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1 Introduction

For standoff underwater explosions, a shock wave forms and propagates through the water and loads the structure with a pressure pulse of high amplitude and short duration. This pressure amplitude decreases with increasing standoff, as shown in Figure 1.

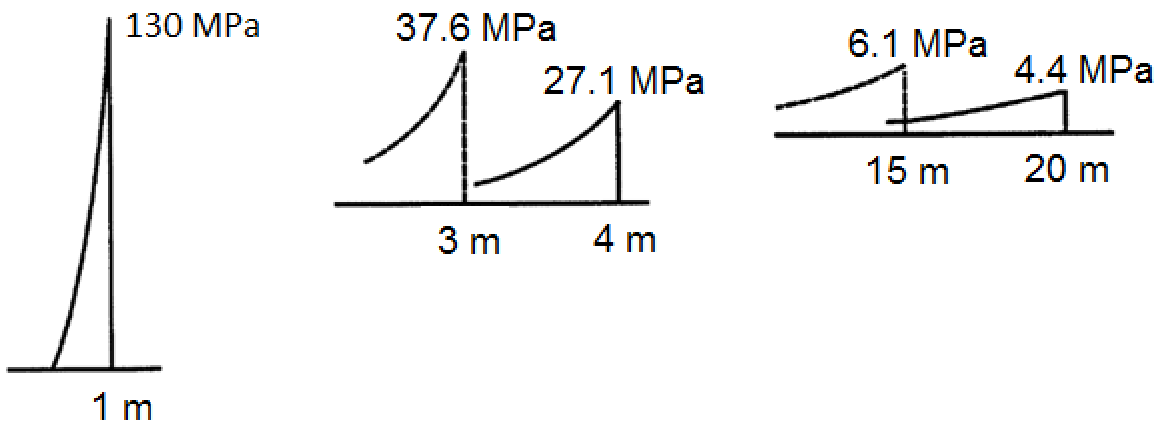


Figure 1: Pressure Distribution around a 10 kg TNT charge at five positions from the point of detonation.

Although it is advantageous to conduct a numerical analysis of the structural response due to such loading, it is often impractical due to the computational cost of creating the models and running the analysis. Historically, shock factors (SF) have been used as a quick estimate of the degree of damage resulting from the shock loading of an underwater explosion. The shock factor is a measure of the energy being imparted on the ship by the shock wave, and is a function of the charge weight, W, and the standoff distance between the charge and ship, R.

The application described in this report applies SF theory to graphically display three detonation zones corresponding to SF limits set by the user. For the purpose of this report these levels are:

- Level 1 (Undamaged Zone): Results in no damage up to possible minor damage such as electric failures;
- Level 2 (Damaged Zone): Minor damage up to general machinery failure and approaching ship failure; and
- Level 3 (Kill Zone): Generally considered lethal to a ship.

This report has been divided into the following chapters. Chapter 2 describes the underlying theory and any assumptions as well as how these methods were implemented for developing UNDEX_Zones. Chapter 3 discusses the code used for UNDEX zone development as well as the usability and functionality of the application. Chapter 4 is a summary of the report and outlines potential future developments.

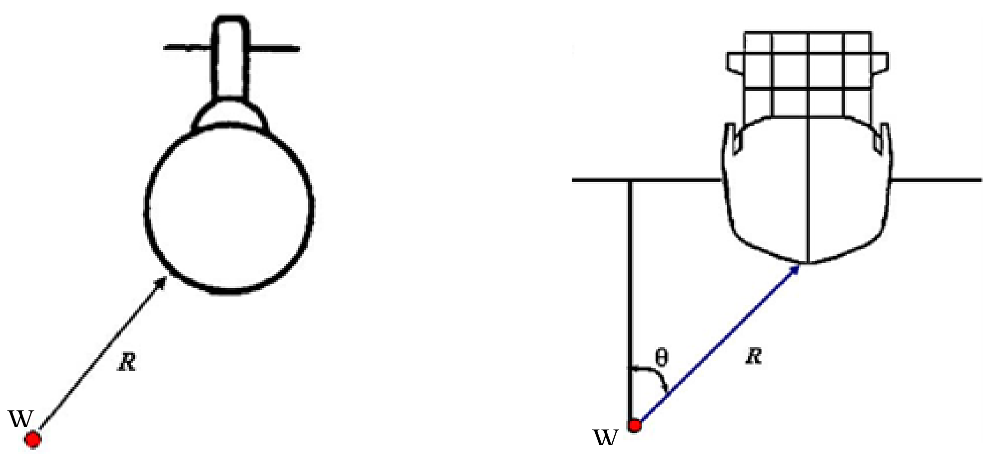
2 Theory for Code Development

The reason for developing UNDEX_Zones was to create a software tool which provides a quick and easily interpreted assessment of the anticipated damage from an underwater explosion for a range of charges and detonation depths. Shock factors have been used as the underlying theory for UNDEX_Zones due to their historical use for quick damage predictions. The tool generates a graphical representation of three detonation zones for a range of charge sizes and detonation depths resulting in varying degrees of damage.

2.1 Shock Factor Calculations

Two commonly used measures of the shock factor are the hull shock factor (HSF) and the keel shock factor (KSF). The HSF is a measure of the energy in the shock wave which can contribute to the damaging hull plating of the vessel. The HSF is a function of the equivalent TNT charge weight, *W*, and the shortest distance between the point of detonation and vessel hull, *R*, as shown by Eq. (1) and illustrated in Figure 2(a). The HSF is generally used as a damage prediction method for submarines.

$$HSF = \sqrt{W}/R \tag{1}$$



(a) (b)

Figure 2: Definitions of the hull shock factor (HSF) and keel shock factor (KSF) [1].

For surface ships the charge position is generally measured relative to the keel, and is referred to as the KSF, as shown by Eq. (2) and illustrated in Figure 2(b). The response for surface ships are primarily vertical, therefore it is necessary to correct for the angle at which the shock wave impacts the target when the charge is not detonated directly under the keel. This is accounted for by θ, which is the angle of incidence between a vertical line and the radial line to the ship keel, as shown in Figure 2(b).

$$KSF = \frac{\sqrt{W}}{R} \times \frac{1+\cos\theta}{2} \qquad (2)$$

For this application it was assumed that the detonation occurs under the keel of the vessel such that the angle of incidence, θ, is 0. This reduces the KSF to the same value as the HSF. The following shock factor levels and anticipated damage associated with each level is shown in Table 1 [2].

Table 1: Anticipated damage based on the magnitude of the keel shock factor [2].

SF (lb, ft)	SF (kg, m)	Anticipated Damage
< 0.10	< 0.22	Very limited. Generally considered insignificant
0.10 – 0.15	0.22 – 0.33	Lighting and electrical failures, possible pipe rupture
0.15 – 0.20	0.33 – 0.44	Increase in damage above, pipe rupture likely, machinery failures
0.20 – 0.50	0.44 – 1.11	General machinery failure
≥ 0.50	≥ 1.11	Usually considered lethal to a ship

A limitation with use of shock factors is that the limits in Table 1 are averages of anticipated damage for a range of targets. This approach does not use structural modelling or calculations, but instead uses generic data found through experiments. To ensure accuracy, the limiting shock factors for the desired target should be obtained. The limiting shock factors of a vessel will depend on its structural design. Factors such as hull thickness, shock hardening, hull geometry, and machinery placement to name a few will affect the shock resistance of the target. Shock factors are not accurate for predicting damage for close proximity explosion loads, which limits UNDEX_Zones use to standoff UNDEX charges. This approach does not include gas bubble collapse loading associated with close proximity UNDEX. This is discussed in more detail in the next section. If the charge is detonated near the seabed or in shallow water the loading on the target can be magnified by reflected waves, which are not accounted for with the use of shock factors. This is especially true for a rigid seabed which can increase the energy available for damage up to 50 percent [3]. It has been reported that for charges less than 20 pounds, approximately 9 kg, only small hull mounted equipment in the immediate area of the detonation is likely to suffer damage [3].

2.2 Gas bubble radius calculations

Upon detonation the products of the explosive create a high pressure gas bubble which will expand until the internal bubble pressure is below the hydrostatic pressure in the surrounding water, at which point it will collapse. The bubble radius at the time of collapse initiation is called the maximum gas bubble radius. From experimental and numerical studies, it has been found that detonations within the maximum gas bubble radius of the structure can lead to structural failure resulting from the added loading on the structure associated with the gas bubble collapse. For small charges, the standoff required to achieve a shock factor of lethal magnitude, such as 1.1, usually lies within the maximum gas bubble radius. For this reason, the lower boundary of the Kill Zone is never less than the maximum gas bubble radius.

The expected gas bubble radius for a charge material of a set size and detonation depth is calculated using Eq. (3), where K_6 is a constant which depends on the charge type, and is determined through experiments [4].

$$R_{max} = K_6 \cdot \left(\frac{W}{D+10} \right)^{1/3} \tag{3}$$

Due to the expense and difficulty of experimentally determining the bubble radius constant, K_6, the gas bubble radii in this application are based on an equivalent charge mass of TNT and the TNT radius constant. The TNT gas bubble constant has been published in the open literature with slight differences in the value [4-6]. For units of meters and kilograms, K_6 = 3.34 is used in UNDEX_Zones. The resulting maximum gas bubble radii provides an adequate approximation for this assessment method.

3 User Interface (UI)

3.1 Code Development

The object oriented code for this application is developed in the data visualization and analysis software tool IDL [7]. Significant advantages to using IDL software for this type of application include:

1. The object libraries used to create the inputs and outputs of the user interface are already developed. This includes predefined codes for developing text boxes, drop lists, control buttons, and plot areas to name a few. This significantly reduces the time required to develop a user interface.

2. Many mathematical functions are already developed within the IDL code, simplifying the code development.

3. The software can be used for free on any system using the IDL Virtual Machine, which can be downloaded from IDLs website [8]. IDL Virtual Machine is available for Windows, Linux, Unix, and Mac operating systems. UNDEX_Zones will be compatible across all these operating systems.

UNDEX_Zones was developed with a main program which calls subroutines for each of the different input and output parameters. The code was developed in such a way that any change in an input parameter results in the updating of all outputs affected by that parameter.

In order to make the code portable it has been compiled into an executable. In IDL the executable file is called a save file and has the file extension *.sav*. This executable allows the application to be run on machines without a licensed version of IDL. This is accomplished by installing free software, IDL Virtual Machine, which is available on ITTs website [8].

3.2 General Layout

The user interface for UNDEX_Zones is shown in Figure 3. For this application it was assumed that the charge is detonated under the keel of the ship.

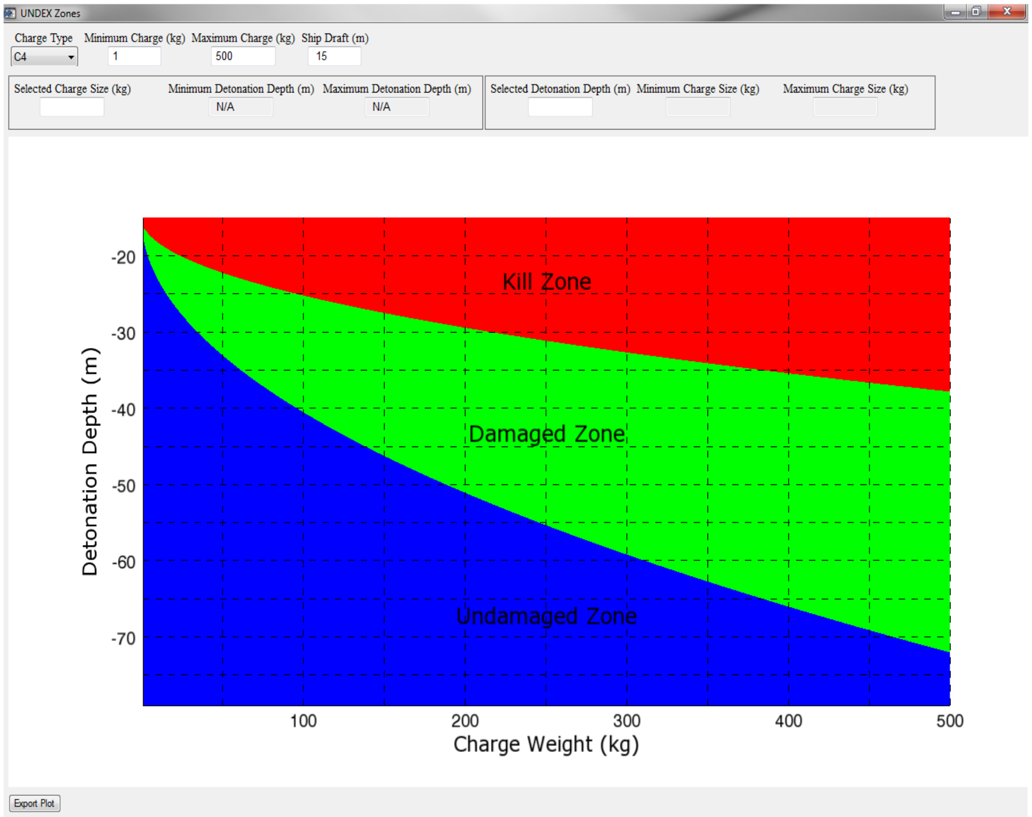


Figure 3: User Interface for UNDEX_Zones.

There are six possible inputs within the UI, including the explosive material, the minimum and maximum charge sizes, the ship draft, a selected charge weight, and a selected detonation depth. The outputs which are displayed on the UI include the detonation depth limits corresponding to the Kill-Damaged and Damaged-Undamaged zone boundaries for the selected charge size and the charge sizes corresponding to the Kill-Damaged zone and Damaged-Undamaged zone boundaries associated with the selected detonation depth. There is also a push button to export the zone plot created by the UI to a bitmap file for adding to reports. The requirements and use of the UI will be discussed in more detail in the following section.

3.3 Requirements to Run the UI

In order to run the user interface you must install the IDL Virtual Machine software available free on ITT's website [8]. You must have all the source code files, files having a *.pro* extension, and the executable file. All source code must be kept in the same directory as the *UNDEX_zones.sav* executable file. This ensures that all program codes can be located when called by the executable. There are also three text files which are required for the application to run, and are explained in more detail in the following section.

3.3.1 Text input files

Three text files provide information for the user interface to run. The files are *input information*.txt, *shock factors.txt* and *charge types.txt* and they are included with the source code. The default directory for selecting a file upon starting UNDEX_Zones is the directory with the executable. Therefore it is preferable to keep these text files in the same directory as the source code and executable file.

Input information.txt, which can be renamed by the user if desired, is the file that should be selected when the user is prompted to select a file upon initiating the application. An example of the *Input information.txt* file is shown below.

Example *Input information.txt* file:

charge types	C:\idl_conversion_codes\SF\Weight vs depth plots\
output dir	C:\Publications\SF\Stage 2\weight vs depth plots\
shock factors	C:\idl_conversion_codes\SF\Weight vs depth plots\shock factors.txt
radius constant	3.3356

This file contains two columns of data separated by a *tab* character. The *tab* character space is required by the code to distinguish the separation of the two columns of information. The first column is a list of keywords, (i.e. charge types, output dir, shock factors, and radius constant) used by UNDEX_Zones to locate information within the file. These keywords cannot be changed, as the application will fail.

The second column contains information corresponding to the keywords. The directories listed for the *charge types* and *shock factors* files must correspond to the location of the *charge types.txt* and the *shock factors.txt* files, respectively, on the user's system. If they are not located by the application, an error message will be displayed and the program will close. The output directory of the plots is where the graphical zone representation will be saved if the export plot button is selected. This can be defined as any existing directory, as the UI will not create a new directory. The bubble radius constant for TNT is used by the application to determine the maximum gas bubble radius for each of the charge weights within the minimum and maximum charge range.

The *charge types.txt* file, as shown below, contains two columns of data which provides the application with the following information:

1. A keyword identifier for the charge materials.

2. The relative effectiveness (RE) factor for the charge materials.

An example *charge types.txt* file is shown below.

N/A	0.0
TNT	1.0
Tetryl	1.25
C3	1.26
C4	1.26
HBX-1	1.68

HBX-3	1.68
H-6	1.68
RDX	1.60
PETN	1.66
Comp. B	1.35
Comp. A3	1.26
HMX	1.70

The first column of keywords is read into the application and is used to select charge types from the charge-type drop list. The RE factor, contained in the second column of the file, is a measure of the strength of the explosive relative to TNT. The values in this file have been taken from open literature and internet sources. The RE factor must be separated by a *tab* character from the charge material name. If the required charge type is not listed in this file it can be added at any line within the file, and the file saved. The RE factor for the desired charge type must also be specified.

The file name *charge types.txt* cannot be changed as it is hardwired into the code. This was done to limit the number of files the user has to select for the program to run. Upon starting the program, the new charge type file will be read by the UI.

The *shock factors.txt* file contains the limiting shock factors as shown below.

Example *shock factors.txt* file:

0.44
1.1

The two shock factor values must be entered in ascending order. If they are entered in descending order then errors will occur in the plot generation. The first shock factor is used as the lower limit for the Damaged Zone, and the second is used for the lower limit of the Kill Zone. The shock factor values should be modified by the user for their desired levels.

Changes to these text files will not be read into the application until it is restarted.

3.4 User Interface Operation

To initiate the user interface, double click *undex_zone.sav.* This will automatically initiate the IDL Virtual Machine software. When the executable is loaded, the user will be prompted to select an input file. Select the *input information.txt* file that has been discussed in the previous section. Ensure the directories in this file are set for the computer being used to run the application. When the input file is loaded by the application, the user interface as shown in Figure 4 will be created. The white area within the UI is the plot area, which will be generated when the required inputs are provided.

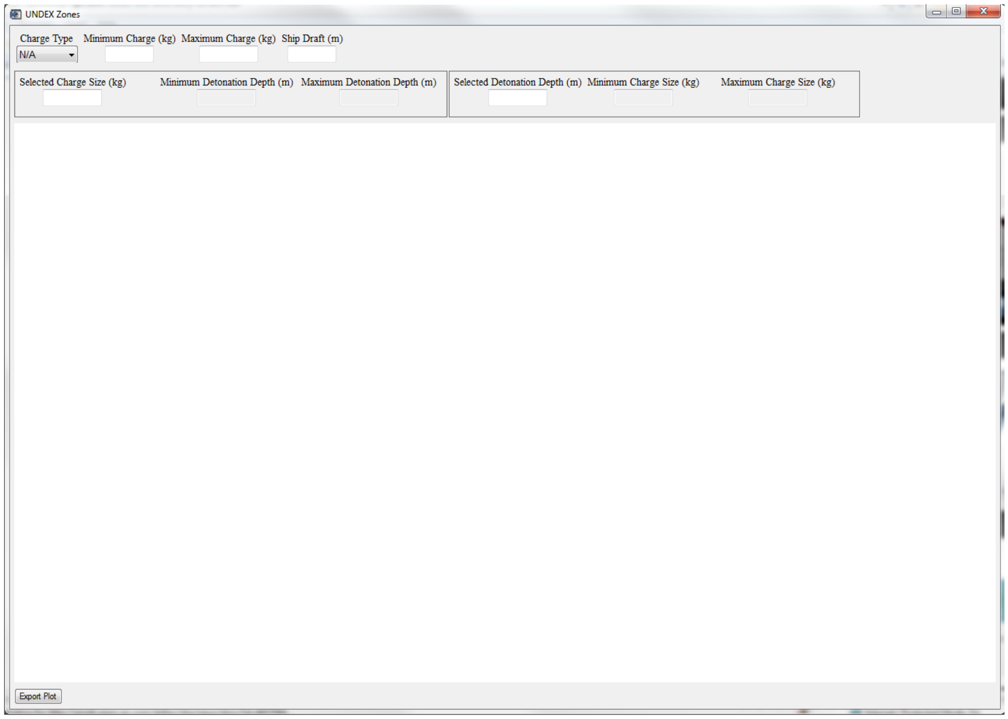


Figure 4: User Interface upon program start-up.

To generate the UNDEX_Zones plot four inputs must be entered. These include the charge type, minimum and maximum charge weights, and ship draft. From the drop list select the charge type, which is the explosive material you are interested in using for your application. The charge type is used to determine the RE factor corresponding to that material, which is then used to determine the equivalent weight of TNT for the shock factor and bubble radius calculations.

The next two inputs are the minimum and maximum charge sizes to be used for graphical representation. These values are entered by selecting the minimum and maximum charge text boxes and entering the desired values. These values define the limits of the abscissa in the zone plot. In order to see a larger plot range it is recommended to enter a minimum charge of a few kilograms and a maximum charge of several hundred kilograms. Keep in mind that the shock factor approach does not predict the overall damage accurately for charges less than 9 kg.

The final input needed to create the zone plot is the ship draft, which forms the upper bound of the vertical axis. A draft of zero can be entered if you are interested in seeing the effect on a system on the surface. The resulting graphical representation of the UNDEX zone plot for 1–1000 kg TNT explosive and a ship draft of 15 m are shown in Figure 5.

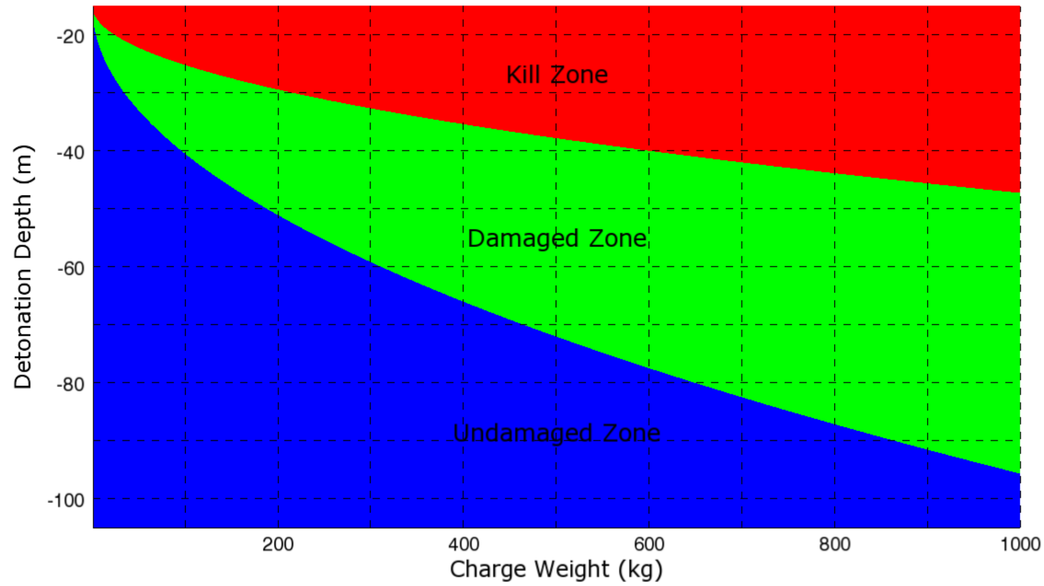
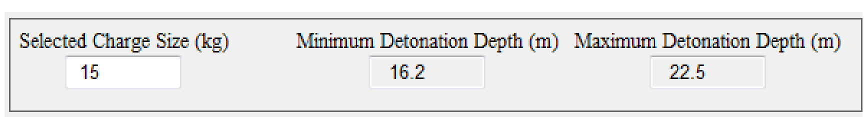


Figure 5: Example UNDEX zone plot for a TNT explosive with a ship draft of 15 m.

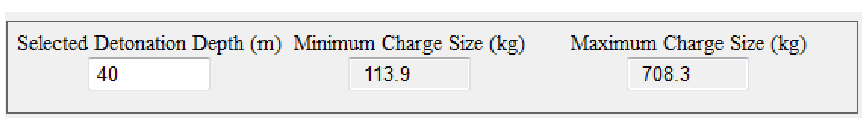
The plot shown in Figure 5 can be saved as a bitmap file by selecting the export plot button, which is located in the bottom left corner of the UI, as shown previously in Figure 3 and Figure 4. The file is saved in the output directory specified in the *input information* text file. The file name is automatically generated and has a name format of *UNDEX zone plot for x with a y m draft*. Where *x* and *y* are the selected charge type and ship draft respectively.

3.5 Optional Inputs

Two optional inputs are the selected charge size and detonation depth. These were created to allow the user to select a certain charge size or detonation depth and obtain the limiting damage zone values. Associated with each of these inputs are two outputs, as shown in Figure 6, where a white background indicates the inputs and a grey background the outputs.



(a)



(b)

Figure 6: Selected charge size and detonation depth input and output options (a) selected charge size and (b) selected detonation depth.

If you are interested in determining the minimum detonation depths at the Kill/Damaged and Damaged/Undamaged zone boundaries for a given charge size, input it in the “Selected Charge Size” box shown in Figure 6(a). This charge size, in conjunction with the charge material and ship draft from previous inputs is used to determine the detonation depths corresponding to the SF limits. These are displayed in the boxes labelled minimum detonation depth and maximum detonation depth.

Similarly, a known detonation depth can be entered in the “Selected Detonation Depth” text box shown in Figure 6(b). This value will be used in conjunction with the charge material, ship draft, and shock factors to determine the minimum charge sizes for the Damaged and Kill zones. If the limits are not contained within the plot area it does not affect these outputs as they are calculated independently from the graphical display.

4 Summary

The methodology and functionality of a simplified user interface, UNDEX_Zones, for predicting the vulnerability of marine vessels to underwater explosion threats has been discussed. Shock factors have historically been used as a method to rapidly assess damage to a ship structure resulting from an underwater explosion. This report provides the background theories that were used in the development as well as the functionality and operating procedures of UNDEX_Zones. UNDEX_Zones has been developed to provide a visual aid in predicting UNDEX damage for varying detonation ranges and charge sizes. The user interface was developed with the visualization software IDL, developed by ITT. With the use of ITTs free “IDL Virtual Machine” program, UNDEX_Zones can operate on any system independent of the operating system or computer model. With no license or system requirements UNDEX_Zones is easily portable unlike most commercial analyses programs.

The application discussed in this report uses the theory of shock factors (SF) to create damage zones for varying detonation depths and charge sizes. The zones are created for SF limits defined by the user.

A goal of the application was to provide a significant amount of flexibility in creating the visual display. User inputs for the visual program include the charge material, the range of charge weights in which the anticipated damage zones will be created, and the draft of the vessel. These inputs are all used in conjunction with the shock factor limits to create the three zones. Other optional inputs include a selected charge weight and detonation depth. For the selected charge weight, the detonation depths bounding the damaged zone are displayed. Similarly for the selected detonation depth, the charge sizes bounding the damaged zone are displayed.

An important feature that will be included in further development of UNDEX_Zones is the influence of off centerline detonations. This will include the angle of incidence, θ, in the KSF calculations.

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List of symbols/abbreviations/acronyms/initialisms

cos	cosine function
D	Charge detonation depth
HSF	Hull shock factor
IDL	Data visualization and analysis software
ITT	Company who develops IDL software
K_6	Gas bubble radius constant
kg	Kilograms
KSF	Keel shock factor
m	meters
MPa	Megapascals
R	Standoff distance between explosive and ship
R_{max}	Maximum gas bubble radius
SF	Shock factor
TNT	Trinitrotoluene
UI	User interface
UNDEX	Underwater explosion
W	Charge weight
θ	Angle between vertical line and straight line between the charge and ship keel
.pro	Program file extension in IDL
.sav	Executable file extension in IDL

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This report describes a new software tool, UNDEX_Zones, which has been developed for rapid, simplified assessment of damage to surface ships from underwater explosion (UNDEX) threats. Damage is determined using shock severity, as measured by the shock factor (SF), which has been found to be correlated with historical data on the level of damage sustained by a vessel. UNDEX_Zones graphically displays damage zones for a range of charge sizes and charge depths for a given explosive type and ship draft. The damage zones include no damage, varying levels of non-lethal disabling damage, and the zone at which would be deemed lethal to a vessel. The present document provides the background theories that were used in the development as well as the functionality and operating procedures of UNDEX_Zones.

Le présent rapport décrit un nouvel outil logiciel, nommé UNDEX_Zones, qui a été conçu pour effectuer une évaluation rapide et simplifiée des dommages sur un navire de surface causés par des explosions sous-marines (UNDEX). L’importance des dommages est déterminée par la gravité du choc, qui est mesurée par le facteur de choc, en corrélation avec les données historiques par rapport au niveau de dommages subis par un navire. Le logiciel UNDEX_Zones affiche les zones de dommages afin d’établir la taille et la profondeur des charges pour un type d’explosif et un tirant d’eau de navire spécifiques. Les zones de dommages comprennent la zone sans dommages, les zones de divers niveaux de dommages majeurs non létaux et les dommages létaux. Le présent document fournit les connaissances théoriques qui ont été utilisées pour la conception, ainsi que les procédures de fonctionnalité et de fonctionnement du logiciel UNDEX_Zones.

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Underwater Explosion, Shock factor, similitude, user interface

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