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Structural Response Caused by Underwater Explosions

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Abstract

Many nations have increased their testing capabilities in underwater explosions (UNDEX) in recent years. This and associated tensions in the world require building the next generation of submarines and aircraft carriers that have high shock absorbing capabilities for keeping personnel and equipment safe or maintain existing ones through retrofitting and strengthening techniques. This undergraduate research is exploring the loading scenario of underwater explosions, the pressure-time history of underwater explosions, and how the loading scenario causes structural response in submerged structures. The scope of this research includes an analysis of various methods used to find variables that describe the shockwave of an UNDEX, mathematical model for calculating the pressure-time history for any given shockwave, a model of a submerged structure made in finite element analysis (FEA) software in order to analyze the structural response caused by and UNDEX. Modeling results will be compared to experimental data obtained from literature. Results of this data can be applied to improve the design and construction of structures that are designed towards UNDEX explosion scenarios and can also be applied to other applications including underwater blast dredging needed for building large scale bridge piers and caissons.

Keywords: Underwater Explosions, Pressure-Time History, Structural Response

1. Literature Review:

1.1 Physical Phenomenon of Underwater Explosions:

There are two main events that occur in an UNDEX; the initial shock wave and the bubble pulse. First, the initial shock wave is produced which is the source of the peak pressure of the explosion. Following the shock wave is the bubble pulse which spans a longer time frame than the shock wave and is caused by the expansion of the hot, condensed gases that are involved with an underwater explosion. The pressure due to the bubble pulse is much smaller compared to the initial shock wave, but it can be the source a significant amount of structural damage due to its higher impulse which is a result of its pressure spanning over a larger amount of time.

1.2 Shock Wave:

The energy of the explosion caused by a chemical reaction is dissipated into a high intensity pressure wave and outward motion of the surrounding water [1]. This initial disturbance of the water is called the shock wave. This pressure wave propagates spherically from the point of explosion and the pressure of the wave decays with distance from the point of the explosion. The pressure also decays over time. This pressure decay over time is exponential and given by equation #1.

$$p(t) = p_m * e^{\frac{t}{\theta}} \qquad (1)\ [2]$$

In this equation, P_m refers to the peak pressure caused by the explosive at a given distance and θ is the time constant which dictates the decay of pressure over time. Both of these values are dependent on a couple variables; type of charge used in the explosion, weight of the explosive charge, and the distance from the charge (calculating these values will be analyzed in a later section).

The decay of pressure is not the same over the whole duration of the shock wave. The pressure decays slower once the pressure reaches a critical value. This is when the pressure is roughly 37% of the peak pressure which occurs after one theta of time has elapsed. Disregarding this change in the rate of decay is not conservative, therefore it should always be taken into consideration. The dotted line in figure #1 shows the slower rate of decay once the pressure has reached the critical value. The following papers can be consulted for similar studies on blast response of regular structures [7-16]

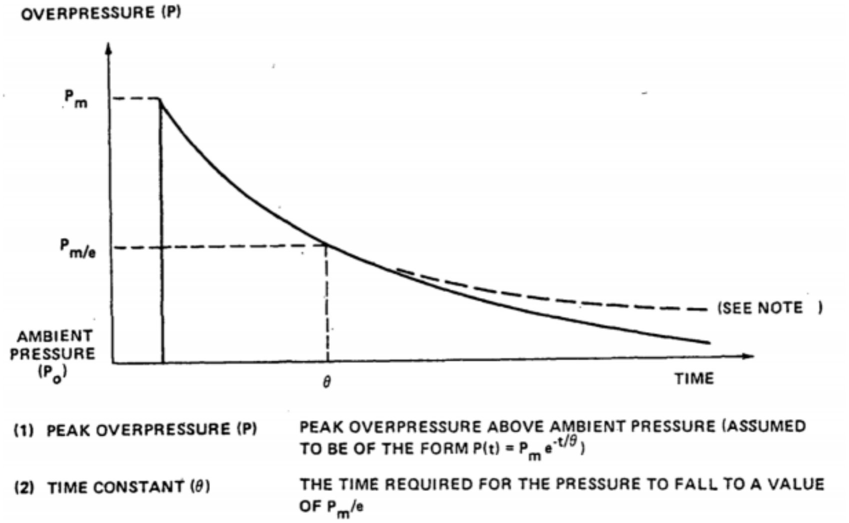


Figure 1: Pressure-Time History of UNDEX. [3]

1.3 Analyzing the Shock Wave:

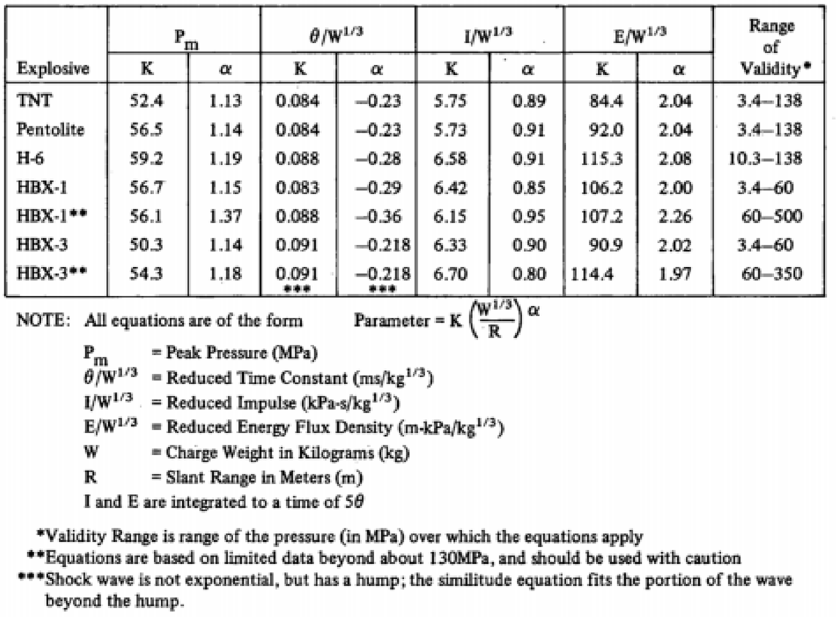
When analyzing the shock wave, there are a few important parameters to consider. Peak pressure and the time constant (θ) are two of those important parameters. These two are of particular importance to this research due to the fact that they are used to find the pressure-time history of a given UNDEX shockwave. Two other parameters that can be used to describe an UNDEX shockwave are the impulse and the total energy of the explosion. These four parameters are dependent on the type of explosive, the weight of the explosive, and the standoff distance of the explosive. The type of explosive is referring to what type of chemicals are used in the explosive charge. There are five different types of explosives that can be characterized by methods used in this research; TNT, Pentolite, H-6, HBX-1, HBX-3. Although these are the five typical explosives that can be parameterized by a method described below, any explosive can be used in any of the methods as long as you can convert the weight of the explosive in terms of TNT.

1.4 Methods for Determining Shockwave Parameters:

1.4.1 similitude constants and coefficients method:

The first method looked at in this research is the similitude constants and coefficients method. In this method, there are unique constants and coefficients for a given explosive type to solve for these parameters using equation #2. In this equation, K (constant) and α (coefficient) are given in figure #2, R is the standoff distance, and W is the charge weight. Scaled distance is often used to simplify this equation, and is equal to the standoff distance, D, divided by the cubed root of the weight, W, which is shown in equation #2 [3]. This method is used to find all four of the parameters of interest in this research.

$$parameter = K * (\frac{W^{1/3}}{R})^{\alpha} \quad (2)\ [3]$$



Explosive	P_m		$\theta/W^{1/3}$		$I/W^{1/3}$		$E/W^{1/3}$		Range of Validity*
	K	α	K	α	K	α	K	α	
TNT	52.4	1.13	0.084	−0.23	5.75	0.89	84.4	2.04	3.4–138
Pentolite	56.5	1.14	0.084	−0.23	5.73	0.91	92.0	2.04	3.4–138
H-6	59.2	1.19	0.088	−0.28	6.58	0.91	115.3	2.08	10.3–138
HBX-1	56.7	1.15	0.083	−0.29	6.42	0.85	106.2	2.00	3.4–60
HBX-1**	56.1	1.37	0.088	−0.36	6.15	0.95	107.2	2.26	60–500
HBX-3	50.3	1.14	0.091	−0.218	6.33	0.90	90.9	2.02	3.4–60
HBX-3**	54.3	1.18	0.091 ***	−0.218 ***	6.70	0.80	114.4	1.97	60–350

NOTE: All equations are of the form Parameter = $K\left(\frac{W^{1/3}}{R}\right)^{\alpha}$

P_m = Peak Pressure (MPa)
$\theta/W^{1/3}$ = Reduced Time Constant ($ms/kg^{1/3}$)
$I/W^{1/3}$ = Reduced Impulse ($kPa\text{-}s/kg^{1/3}$)
$E/W^{1/3}$ = Reduced Energy Flux Density ($m\text{-}kPa/kg^{1/3}$)
W = Charge Weight in Kilograms (kg)
R = Slant Range in Meters (m)
I and E are integrated to a time of 5θ

*Validity Range is range of the pressure (in MPa) over which the equations apply
**Equations are based on limited data beyond about 130MPa, and should be used with caution
***Shock wave is not exponential, but has a hump; the similitude equation fits the portion of the wave beyond the hump.

Figure 2: Similitude Constants and Coefficients Chart. [3]

1.4.2 nomogram method:

The next method looked at in this research is the nomogram method which involves reading the parameter values from a nomogram chart [3]. This requires the knowledge of standoff distance and charge weight just like the similitude constants and coefficients method. This nomogram is read by creating a line that connects the standoff distance and the charge weight values. This line will intersect the columns that are towards the middle of the nomogram. Where this line intersects the columns, the parameter values are given. Unlike the similitude method, this only finds parameters for underwater explosions using TNT, any other type of charge must be converted into equivalent weight of TNT. This method is used to find all four of the parameters of interest in this research.

1.4.3 other methods:

There were two alternative methods that could be used in order to find various parameters that describe an UNDEX shockwave. One of them is used to find the peak pressure of the shockwave. These equations are displayed as equations 3 and 4. These equations are described in the Smith textbook and are fitted to experimental data [2]. The first equation is valid for scaled distances ranging from 0.05 to 10.0, while equation #4 is valid for a range of 10.0 to 50.0.

$$p_m = \left[\frac{355}{Z} + \frac{115}{Z^2} - \frac{2.44}{Z^3}\right] bar \quad 0.05 \leq Z \leq 10 \tag{3} [2]$$

$$p_m = \left[\frac{294}{Z} + \frac{1387}{Z^2} - \frac{1783}{Z^3}\right] bar \quad 10 \leq Z \leq 50 \tag{4} [2]$$

The final method analyzed in this research is the integration method. This is used to find the impulse of the UNDEX shockwave and the total energy of the explosion [2]. The impulse is given by equation #5 and integrates the pressure-time equation, equation #1, and integrates this with respect to time. The total energy given by equation #6 is similar but integrates the square of the pressure-time equation with respect to time and is then multiplied by a constant. This constant is the inverse of the density of water multiplied by the speed of sound in water.

$$I = \int_0^{6.7\theta} p(t)dt \tag{5} [2]$$

$$E = \frac{1}{\rho_w c_w} \int_0^{6.7\theta} p(t)^2 dt \tag{6} [2]$$

2. Methodology:

2.1 Kwon and Fox Experiment:

In order to compare the findings of this research to experimental observation, experimental data was found in the open literature. This data came from an experiment conducted in 1992 by Kwon and Fox with an UNDEX was placed 12ft under the surface and acted upon a hollow aluminum cylinder [4]. Their physical experiment is described in figure #3 with 25 ft (7.62 m) for standoff distance, 60 lbs (27.3 Kg) for weight of charge, and HBX-1 for the type of charge. There are various sources of data that came from this experiment. There is the peak pressure of the shock wave that was found by placing pressure sensors at the standoff distance point. These pressure sensors also measured the pressure time history of the shockwave. Also, there were strain gauges attached to the cylinder to measure structural response.

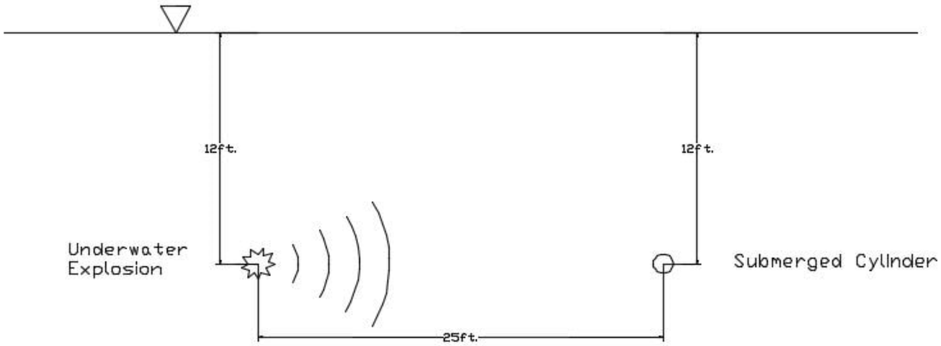


Figure 3: Physical description of Kwon + Fox experiment.

2.2 Parametric Analysis of the Explosion:

There exists many methods of finding the parameters to describe an UNDEX shockwave which are described in the literature review. Because of this, we wanted to know how accurate these different methods are when compared to each other and also how they compare to experimental data. Using Microsoft Excel, tables and charts were created to compare the different methods. A separate excel sheet was used for each of the parameters; peak pressure, time constant, impulse, and total energy of the explosion. The explosive type of TNT was used for these calculations. This is because weight of TNT can be used for each of these methods, there is no conversion necessary.

Three different methods can be used to find peak pressure; similitude constants and coefficients method, nomogram method, and using the peak pressure equations. Peak pressure was calculated and compared for each method using various scaled distances. The scaled distances ranged from 0.2 to 50. For the time constant, theta, calculation can be done by two different methods; similitude constant and coefficient method and the nomogram method. The time constant was calculated using each method similar to how peak pressure was calculated, using a wide range of scaled distances.

Impulse and total energy both have the same three methods used for calculation; similitude constants and coefficients method, nomogram method, and the integration method. To find impulse and total energy using the similitude method and the nomogram method, the same process was used as was used to find peak pressure and the time constant. In order to use the integration method, we needed to set proper bounds for integration. The total time range used for integration was from time zero to time 6.7θ. Because the pressure equation changes once the explosion reaches the critical time of theta, two separate bounds of integration are used. The first bound is from time zero to time theta integrating the original pressure equation, and the second bound is from time theta to time 6.7 theta integrating the modified pressure equation that takes into account the reduced rate of decay, equations #7 and #8, where p(t)' is the modified pressure-time equation that is used to account for the reduced rate of decay. The similitude method was used to find the peak pressure and theta values that are used to solve for the integration method. After completion of the integration method, these values are compared.

$$I = \int_0^{\theta} p(t)dt + \int_{\theta}^{6.7\theta} p(t)'dt \tag{7}$$

$$E = \frac{1}{\rho_w c_w}[\int_0^{\theta} p(t)^2 dt + \int_{\theta}^{6.7\theta} p(t)'dt\,] \tag{8}$$

2.3 Pressure-Time History of the Shockwave:

To fully characterize the shock wave, a pressure-time history needs to be determined. To do this, a mathematical model was created in MATLAB programming language. This program takes in values for type of explosive, weight of the explosive, and standoff distance. Using the similitude coefficient method, peak pressure and the time constant (θ) are found. Pressure from time zero to the critical time of θ is any given by equation #1. Once the time reaches θ, the pressure decreases at a slower rate. Once this is accounted for, pressure at any given time in the duration of the shockwave can be found.

2.4 Finite Element Model:

In order to study the structural response of a submerged structure, a finite element model of a submerged structure was used through the finite element analysis software, ABAQUS. The ABAQUS documentation contains an example problem, 9.1.4, that is based off of the original Kwon and Fox experiment and is used to predict the structural response of a submerged structure that experiences loading of an acoustic shock wave caused by and UNDEX [5]. There are 2 geometric structures in this model. One is the submerged structure, which is modeled as a hollow cylinder and is meshed with the properties of 6061-T6 aluminum. The other geometry is of the water surrounding the submerged structure and is meshed with the properties of water. Figure #4 shows the finite element model with the top portion of the water removed for clarity.

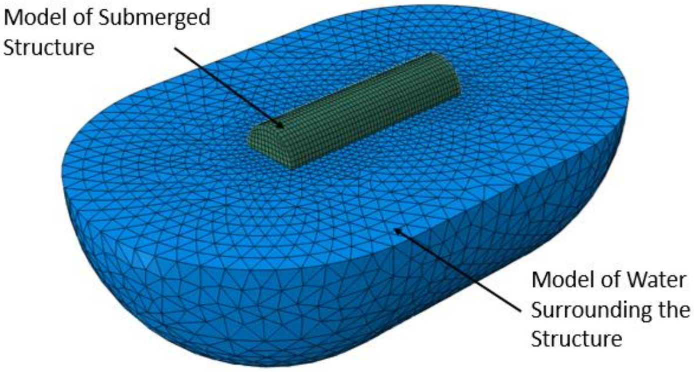


Figure 4: Geometric model made in FEA Software Abaqus.

Once this geometry is created, the shockwave loading needs to be applied to the structure. This loading was modeled as an “incident wave” and described using “incident wave interaction” in ABAQUS. The amplitude of this loading is described by the pressure-time history of the UNDEX that was found through the mathematical model.

3. Results:

3.1 Parametric Analysis:

After analyzing and comparing the various methods that are used to solve for the different variables that describe the shockwave of an UNDEX, it was found that all of the load prediction methods compare well with each other, follow the same trends, and are conservative when compared to experimental data. When looking at the experimental data, the only measured data that was found from the Kwon and Fox Experiment that can be used for comparison was peak pressure [4]. Figure #5 shows the comparison between the different methods used to find peak pressure and the experimental data.

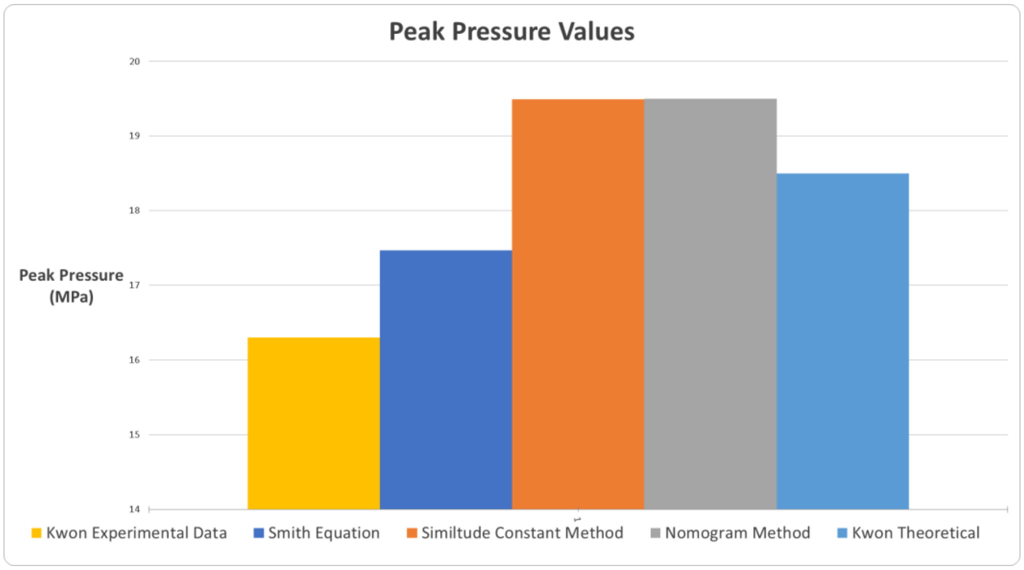


Figure 5: Comparison of Theoretical and Experimental Peak Pressure Values.

3.2 Pressure-Time History:

The results of the mathematical model that produced the pressure time history was compared to the Kwon and Fox experimental data [4]. The comparison of this data is shown in figure #6. The theoretical peak pressure found was larger than the peak pressure found from the Kwon and Fox experiment, which agrees with the parametric analysis. Theoretical pressure was consistently larger or more conservative than the experimental data up until the critical time of theta. After this, the theoretical pressure had a smaller amplitude but still very close in value. The theoretical data produced by this mathematical model compared very well overall to the experimental data showing that the mathematical model that was created in this research is accurate.

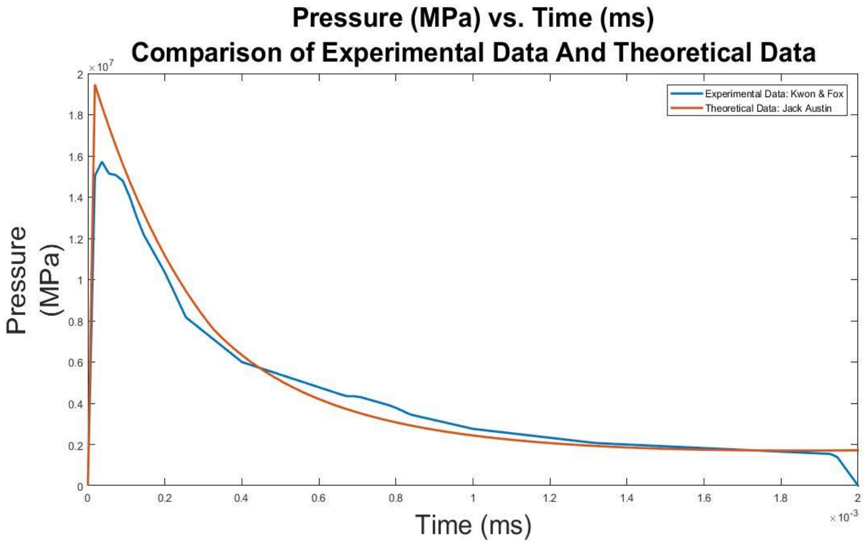


Figure 6: Comparison of experimental data gathered by Kwon and Fox [4] with theoretical data found by mathematical model.

3.3 Structural Response:

Results were obtained by running the Finite Element Analysis. Through ‘post processing’, visual representations of the structural response were created by ABAQUS. Figure #7 is the visual representation of stresses within the structure when it is subjected to an UNDEX load. Stresses within the Aluminum structure are shown by the color gradient and correspond to a certain amplitude of stress that can be read off of the chart within figure #7. For comparison, figure #8 was added. This figure was created by a similar model created by Adam Evans [6].

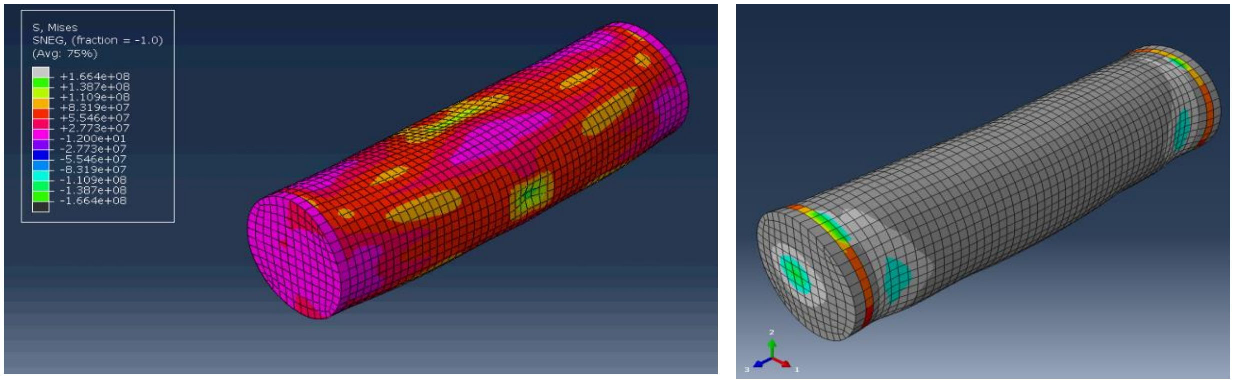


Figure 7: Preliminary Structural Response from this research (Left) and Structural Response Produced by Adam Evans (Right) [6].

At this point in the research, the preliminary results from the structural response needs additional work. It is anticipated that the stresses and deformation build up near the end caps of the structure as observed in the Kwon and Fox experimental data. However, in our current model, the stresses and deformation build up towards the center of the structure (figure #7) [4]. Solutions to address this discrepancy are currently being investigated.

4. Conclusion:

When analyzing the results of this research, there are two main areas of success and one main area that still needs additional work. One of the areas of success was the analysis of the load prediction methods used to find the important parameters needed to describe the shockwave. It was found that all of the load prediction methods for finding all of the different variables compare very well with each other and are conservative when compared to experimental data. This is important to engineers in order to know that their calculations will be relatively accurate and conservative to experimental measurements. It is also important to know that all of these load prediction methods agree very well with each other. This means that whichever method that is chosen to calculate these parameters will provide acceptable results. The other area of success in this research was the mathematical model of the pressure time history. This model can be applied to a very wide variety of underwater explosions for various explosive types, weights, and stand off distances. This model also proved to compare very well to experimental data. This mathematical model helped create the loading scenario to find structural response in this research and can easily be applied by engineers in the design world to create their loading scenario.

There was one topic in this research that was not as successful as the others, and this was the interpretation of the FEA results. At this point in the research, the preliminary results from the structural response needs additional work and this is described in the results section. Remedies needed to address this discrepancy are currently being investigated.

5. Acknowledgements:

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