TECHNICAL REPORT
TR-NAVFAC-EXWC-EV-1802
MARCH 2018

MODELING A ROBUST CAISSON STRUCTURE TO RESIST EFFECTS FROM BLOW-IN-PLACE OF UNDERWATER UNEXPLODED ORDNANCE

Strategic Environmental Research and Development Program
Project MR-2648

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REPORT DOCUMENTATION PAGE

FORM APPROVED
OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED *(From – To)*
January 2018	Final Report	April 2016 to March 2018

4. TITLE AND SUBTITLE
MODELING A ROBUST CAISSON STRUCTURE TO RESIST EFFECTS FROM BLOW-IN-PLACE OF UNDERWATER UNEXPLODED ORDNANCE

SERDP Project Number: MR-2648

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER
SERDP Project Number: MR-2648

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Facilities Engineering and Expeditionary Warfare Center
1100 23rd Avenue, Port Hueneme CA 93043-4301

8. PERFORMING ORGANIZATION REPORT NUMBER
TR-NAVFAC-EXWC-EV-1802

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Strategic Environmental Research and Development Program (SERDP)
4800 Mark Center Drive, Suite 17D03
Alexandria, VA 22350-3605

10. SPONSOR / MONITOR'S ACRONYM(S)
SERDP

11. SPONSOR / MONITOR'S REPORT NUMBER(S)
MR-2648

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution A, Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This project was funded as an Exploratory Development or Limited Scope (SEED) project by the Strategic Environmental Research and Development Program (SERDP). The objective of this project is to develop a design for a robust caisson structure that effectively mitigates blast effects generated by underwater explosions, in particular munitions that cannot be moved due to explosive safety concerns. The Naval Facilities Engineering Command Engineering and Expeditionary Warfare Center (NAVFAC EXWC) performed computer modeling and simulation to develop and validate various concepts for a caisson structure using Dynamic System Mechanics Advanced Simulation (DYSMAS) software. The benefits of using a caisson structure to mitigate the blast effects from underwater blow-in-place (BIP) operations are: significantly reducing the amount of real estate/waterways requiring closure during a BIP operation, a vast reduction of the blast loading on nearby infrastructure, and nearby marine life.

15. SUBJECT TERMS
SERDP, EXWC, DYSMAS, Caisson, UNDEX, BIP, Model, Simulation, Blast, TNT, Underwater

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified					Joseph Trotsky
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
U	U	U	UU	23	(805) 982-1258

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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ACRONYMS

BIP	Blow in Place
DYSMAS	Dynamic System Mechanics Advanced Simulation
DRI	Desert Research Institute
DTRA	Defense Threat Reduction Agency
EXWC	Engineering and Expeditionary Warfare Center
FSI	Fluid-Structure Interaction
HFPB	High-Fidelity Physics Based
MUSCL	Monotonic Upwind Scheme for Conservation Laws
NAVFAC	Naval Facilities Engineering Command
SERDP	Strategic Environmental Research and Development Program
SPAWAR	Space and Naval Warfare Systems Command
TNO	Applied Scientific Research
TNT	Trinitrotoluene
UNDEX	Underwater Explosions

KEYWORDS

Blast, BIP, Caisson, DYSMAS, Model, Simulation, TNT, Underwater, UNDEX,

ACKNOWLEDGEMENTS

We gratefully thank the Strategic Environmental Research and Development Program under the direction of Dr. Herb Nelson. The technical assistances on DYSMAS from Naval Surface Warfare Center, Indian Head Division, particularly from Mr. Roger Ilamni, Reid Mckeown, Gregory Harris and Adam Goldberg are also greatly appreciated.

1.0 ABSTRACT

1.1 Objective

Underwater munitions in shallow waters represent a significant threat to human health due to incidental contact from recreational users and in some circumstances commercial dredging operations. Technologies are needed to cost-effectively and safely dispose of these munitions. Current blow-in-place (BIP) techniques result in the closure of significant portions of waterways and adversely impact the marine life.

This project consisted of a modeling and simulation effort to investigate the reduction of blast pressure waves from installing a robust caisson structure around an underwater BIP detonation. This work is responsive to MRSON-16-01 under topic: "Cost-Effective Recovery and Disposal". A blast shield (e.g. a robust caisson structure) will allow for a BIP of underwater munitions that cannot be moved due to explosive safety concerns and will significantly reduce any impact to marine life or nearby structures.

The objective of this project was to develop a design for a robust caisson structure that effectively mitigates blast effects generated by underwater explosions (UNDEX), in particular munitions that cannot be moved due to explosive safety concerns. Specific objectives are to: (1) demonstrate a reduction in UNDEX blast pressures and acoustics with the use of the shielding concept over a baseline case; (2) determine a performance requirement that optimizes mitigation efficacy; and (3) quantify a relation between charge size and shielding performance.

1.2 Technical Approach

The Naval Facilities Engineering Command Engineering and Expeditionary Warfare Center (NAVFAC EXWC) performed computer modeling and simulation to develop and validate various concepts for a robust caisson structure using Dynamic System Mechanics Advanced Simulation (DYSMAS) software, a fully-coupled and extensively validated hydro-code developed in cooperation between the U.S. and Germany governments (Naval Surface Warfare Center, Indian Head Technical Report 3062, 2010). The DYSMAS modeling identified the most effective conceptual designs for mitigating blast effects of UNDEX generated from BIP operations. Four types of blast mitigation conceptual designs with various configurations were modeled. Significant reductions in terms of blast peak pressure, impulse intensity, and energy flux density from the baseline scenario were demonstrated by the DYSMAS simulation results.

1.3 Results

DYSMAS simulations showed that increasing the amount of air around the BIP could reduce the blast effects of the UNDEX. The proposed air tank (Type IV) mitigation is considered the best candidate for further development. This innovative design splits the total blast wave energy into multiple smaller amount of shock waves that arrive at the target locations at the different times, resulting in much lower blast peak pressures and impulses. In addition, the air tank resists the shock waves directly coming from the bottom of the tank so that the material strength of the tank

(*e.g.* steel or concrete) can be effectively utilized to ensure the safety of the air tank itself during the BIP operations.

The tube structure (Type III) is also shown to work very well in shallow waters, particularly in the beaches or the surrounding areas of bridge piers, dry docks or other infrastructure facilities. The double hull with air (Type II) is the modification of traditional air bubble curtain mitigation that could survive only up to 5.0 lb. Trinitrotoluene (TNT), according to the literature reviews. The DYSMAS simulations confirmed that Type II was completely destroyed at 20 lb. TNT. This was because the double hull with air (Type II) had to resist the lateral blast pressure impacts. In general, the lateral resistance capacity of a double hull structure is much less than that in the axial direction (see Type IV).

1.4 Benefits

The benefits of using a robust caisson structure to mitigate the blast effects from BIP operations are: significantly reducing the amount of real estate/waterways requiring closure during a BIP operation, a vast reduction of the blast loading on nearby infrastructure, and a significant decrease in the lethal blast dosing inflicted on nearby marine life.

2.0 OBJECTIVE

The objective of this project was to develop a design for a robust caisson structure that effectively mitigates blast effects generated by UNDEX, in particular munitions that cannot be moved due to explosive safety concerns. Specific objectives are to: (1) demonstrate a reduction in UNDEX blast pressures and acoustics with the use of the shielding concept over a baseline case; (2) determine a performance requirement that optimizes mitigation efficacy; and (3) quantify a relation between charge size and shielding performance.

This project consisted of modeling and simulation efforts to investigate the reduction of blast pressure waves from installing a robust caisson structure around an underwater BIP detonation. This work is responsive to MRSON-16-01 under topic: "Cost-Effective Recovery and Disposal". The caisson structure will act as a blast shield that will significantly reduce impact to marine life or nearby infrastructure and will significantly reduce the explosive arcs which may allow for a BIP of underwater munitions that cannot be moved due to explosive safety concerns.

The degree of successfulness of developing a caisson structure that effectively mitigates blast effects is relative to the distance in reduction of standoff distances for divers, underwater infrastructure, and marine life. The computer modeling and simulation investigation does show that a significant reduction of blast pressure waves can be achieved; therefore, we deem this effort as successful. However, more computer and experimental modeling and simulation efforts should be performed to quantify a relation between charge size/location and optimized caisson performance, which is proposed herein as the Phase II of this R&D project.

3.0 BACKGROUND

Underwater munitions in shallow waters represent a significant threat to human health due to incidental contact from recreational users and in some potential circumstances commercial dredging operations. Technologies are needed to cost-effectively and safely recover munitions in the underwater environment.

While retrieval of non-fuzed munitions would typically occur, the explosive risk for fuzed munitions is too high. In this case a BIP detonation may be the most cost effective option available today. The use of in-situ detonation for assumed fuzed munitions is waning due to blast pressure waves and acoustics that may potentially harm nearby infrastructure (e.g. piers, dry docks, or undersea pipelines/communication cables) and sensitive biota (e.g., whales, sea turtles etc.). Techniques applicable for non-explosive underwater neutralization (i.e., remotely operated water jet cutting) are being developed, however, they are not proven and may leave or expose explosive fillers providing potential chemical risks to the surrounding environment. Mitigation of these effects requires understanding of the underlying phenomena in order to address it.

The mechanics of an UNDEX are similar to that of an aboveground detonation. The explosion is characterized by an instantaneous release of energy that immediately propagates through the surrounding medium via a high velocity shock front. At a given reference point some distance from this detonation, the ambient pressure is instantaneously raised to the peak shock pressure, and then exponentially decays over the duration of the loading. The area under the pressure-time history curve is referred to as the impulse, and can have an equally, if not more important, effect on structural response of impacted infrastructure as the peak shock load. While the primary shock wave propagation underwater can be nominally related to open-air explosions with similar scaled relationships and equations of similitude, the degree of applied pressure and impulse from the blast wave can be an order of magnitude greater underwater. This fact results in safe standoff distances for divers, underwater infrastructure, and marine life that far exceed those associated with above ground explosions for equivalent explosive weights.

Additionally, a secondary effect of underwater detonations that must be considered in any hazard assessment is the secondary pressure pulses generated by the successive cavitation collapses of the gas bubbles formed by the explosive by-products. After the primary detonation, the consumption of the gaseous by-products results in the formation of a massive gas bubble near the location of the detonation. The expansion of this bubble is ultimately impeded when the ambient water pressure exceeds the internal pressure of the bubble, at which point the cavity violently collapses and produces a secondary shock wave through the water. Though the peak pressure of this secondary wave will have a lower peak shock pressure than that of the original detonation, the duration can be longer which could produce significant impulse on surrounding infrastructure. This process of cavitation expansion and collapse producing a shock wave is repeated with diminishing magnitude until the environment equalizes.

The pressure wave at a given target location from a detonation is also highly affected by the relative locations of the explosion source and the target to both the water surface as well as the sea bottom. In open air explosions, the magnitude of the peak pressure in the blast wave is

nominally increased by a factor of 2.0 due to ground reflections given that the distance to the target is sufficiently greater than the height of burst. A similar effect is seen in underwater detonations, but the less than ideal reflection of the sea bottom has shown that magnification factor to be on the order of 1.2 to 1.7 depending on the sea bottom composition [1].

In order to mitigate the hazardous effects of UNDEX, the magnitude of the peak pressure in the initial shock wave must be mitigated and the cavitation effect must be minimized. Potential solutions to mitigate the effects at the explosion source must attempt to dissipate the energy released by the detonation in a less harmful fashion, such as creating turbulence in the wave front, application of protective structures with impedance layers to contain the explosion energy, and redirection of the released energy. The optimization of any such solution must be coupled with numerical simulation of the problem in order to economically target a real design solution.

The most well-known mitigation solution for UNDEX at the explosion source is the use of an air bubble screen, or air bubble curtain around the explosive item at the time of detonation. Laboratory tests have shown that for small explosive weights, 2 kg of TNT in this case, the use of air bubble can reduce peak pressure, impulse, and energy flux density by a factor of 2.0 [2]. Much research has been invested in this technology, but questions still remain regarding the effectiveness for larger explosive weights of more than 5.0 lbs., as well as environmental effects in real world scenarios (e.g., effects of current, surface condition, terrain slope, etc.).

Alternatively, other source mitigation solutions include the use of protective layers, low impedance curtains, or an air bell/caisson concept. The Netherlands Organisation for Applied Scientific Research (TNO) [3] addressed these alternative solutions after an exhaustive literature review, and conducted a series of scaled tests to quantify the source mitigation effectiveness against UNDEX. The results of these tests [4] did not generate the mitigation effectiveness previously demonstrated by the use of the air bubble curtain. The tests primarily addressed the caisson concept, which used a semi-frangible weak structure to generate the air bell. This resulted in minimal energy dissipation via plastic deformation of the structure, and had a non-substantial impact on the reduction of the peak shock pressures generated (on the order of 15% to 35%, depending on the scale of the test). Additional tests with the use of internal impedance materials (other than air) such as fire extinguishing foam or polyurethane foam showed an even smaller reduction in the peak shock pressures and associated safety distances. All of these tests provide pressure-time histories from multiple gauges. The design of the caisson structure itself is identified as an issue in this test series, as it provided little to no containment of the blast effects. A more robust caisson structure that would better contain the effects is a promising solution to the mitigation problem at hand.

In addition to the aforementioned caisson and impedance layer tests, the TNO series also examined the use of covering the explosive item with protective layers upon detonation. This showed promise in the TNO study using hydro pebbles, but the quantity required to produce the desired mitigation result makes the concept impractical to apply full scale. A recent study funded by SERDP and executed by Space and Naval Warfare Systems Command (SPAWAR) [5] also addressed this concept by examining the effectiveness of using a bubble curtain in combination with covering a UXO with sea-floor material during an UNDEX BIP.

4.0 MATERIALS AND METHODS

The computer modeling and simulations with the DYSMAS fluid-structure interaction (FSI) code were the primary methodology in this R&D project. Developed as the collaboration between the U.S. and Germany governments since 1995, DYSMAS is a fully-coupled, government-owned and developed hydro-code for predicting weapons effects and structural responses (Naval Surface Warfare Center, Indian Head Technical Report 3062, 2010). It is the most extensively validated code for UNDEX, comprising of Gemini and PARADYN codes. Gemini is an Euler equation solver designed to simulate UNDEX, focusing on capturing explosion shocks and predicting UNDEX bubble phenomena. The fluid algorithm in Gemini is a higher order Godunov method, based on a time-split Monotonic Upwind Scheme for Conservation Laws (MUSCL) type scheme, running on a fixed Cartesian grid for multiple materials. Included within Gemini are algorithms that facilitate interaction of the Euler domain with embedded bodies of arbitrary shape. Using these algorithms, Gemini is coupled to a structural code of PARADYN to predict the response of nearby structures such as ships and submarines (Naval Surface Warfare Center, Indian Head Technical Report 2500, 2003).

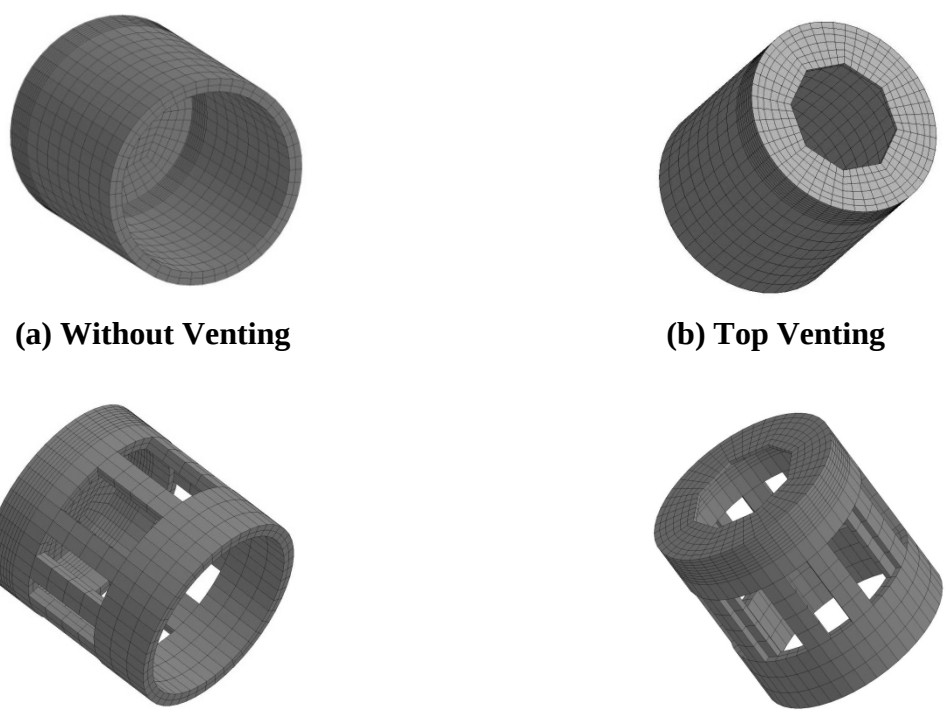
A three-dimensional (3-D) high-fidelity physics based (HFPB)-model was created using DYSMAS to simulate blast wave propagations in the water to the target locations with or without taking into account FSI in the model. Since this R&D project was funded as a SERDP Exploratory Development (SEED) or Limited Scope project, the focus of this effort was to explore and identify the innovative ideas that could contain or minimize the blast wave effects of UNDEX using robust caisson structures. Thus, it was decided that the full FSI effects would be analyzed in a future multi-year project, if additional funding could be warranted. Therefore, since the 3-D HFPB model without FSI was symmetrical in the horizontal direction, 2-D DYSMAS models were used herein for computational efficiency.

In 2-D models, the default material properties of air, water, steel and sand were used, while the explosives were modeled with both unburned and burned TNT material properties, as shown in Table 1. The DYSMAS models also contained about 1.0 m (3.28 ft.) air above the water surface with the non-reflective (i.e. free) boundaries at the top of the air as well as on the vertical (far) edge of the models in order to mimic an infinite air and water extent, respectively. The free boundary conditions prevented high blast energy from reentering into the models in a computational domain and eliminated unreasonably magnifying the blast effects in the models. The reflective boundaries considering a second order wall treatment (i.e. wall2) were assigned on the vertical (center) edge of the model due to the symmetrical feature of 3-D modeling. The "wall2" reflective boundaries were also assigned at the model bottom to represent the hard rock seabed.

Table 1: Default Material Properties in 2-D DYSMAS Models

Material	Mat # Model File Name	Equation of State Type	Density gram/cm^3	(lbs. /ft.^{3})	Parameters
Air	air.mtl	Gamma Law	0.0013	(0.0812)	Gamma = 1.4
Water	tillwater.mtl	Tillotson	1.0	(62.4)	Omega = 0.28
Steel	steel4.mtl	Miegrunisen	8.129	(507.0)	Gamma = 1.6
Sand	sand4.mtl	Miegrunisen	1.9	(119.0)	Gamma = 0.97
Unburn TNT	tntsolid.mtl	Burn	1.63	(102.0)	Factor = 0.95
Burn TNT	tnt.mtl	JWL	1.63	(102.0)	Omega = 0.30

The DYSMAS computer simulations were performed to evaluate the baseline scenario and four types of blast mitigations. The baseline scenario was selected to represent a typical BIP. Type I was based on previous experience with air blast mitigation, Type II was selected based on literature review, and Type III and IV were selected based on innovated ideas. Type I is a steel single hull having four configuration designs; (a) without venting (b) with top venting (c) with side venting, and (d) with full venting. Type II is a steel double hull having three configuration designs; filled with air, sand, or water. Type III is a tube structure for shallow water applications and Type IV is an air tank for deep sea applications (see Figures 1 to 3). All these blast mitigations have an overall dimension of approximate 2.44 m (8.0 ft.) in (outer) diameter and 2.44 m (8.0 ft.) high.



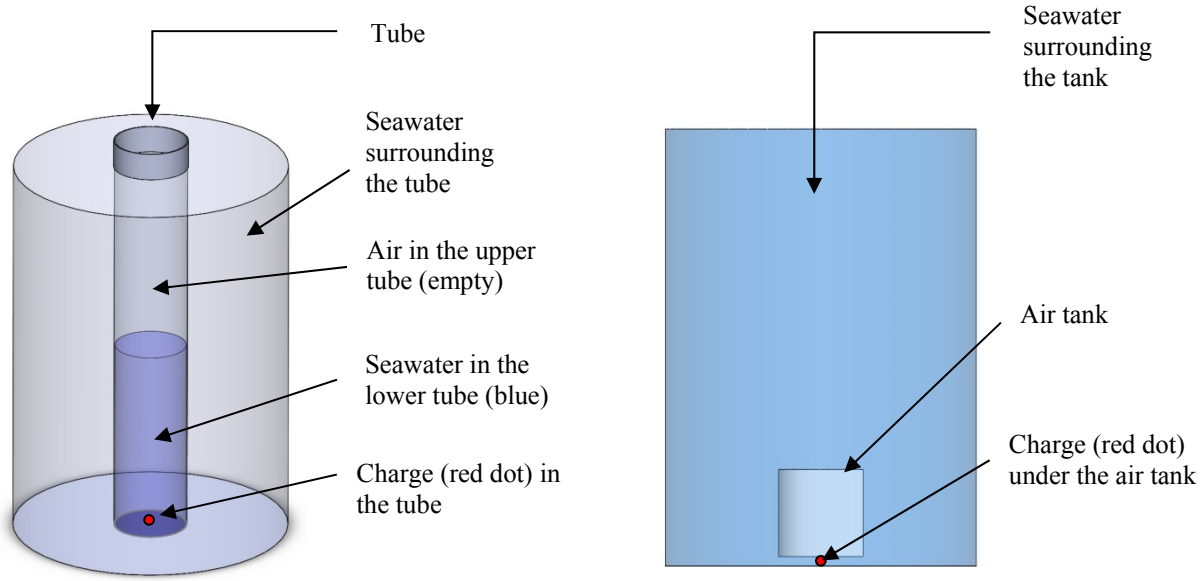
(a) Without Venting **(b) Top Venting**

(c) Side Venting **(d) Full Venting**

Figure 1: Type I Blast Mitigation – Steel Single Hull

Type II Steel Double Hull with Air, Sand, or Water between Inner and Outer Hulls

Figure 2: Type II Blast Mitigation – Steel Double Hull



Type III Tube Structure **Type IV Air Tank Structure**

Figure 3: Types III (Tube) and IV (Air Tank) Blast Mitigations

5.0 RESULTS AND DISCUSSIONS

5.1 Baseline, Results from DYSMAS Simulations

The 3-D DYSMAS baseline model has a water depth of 12.8 m (42.0 ft.) and a horizontal dimension varying from 30.48 m (100 .0 ft.) to 304.8 m (1,000.0 ft.). The charge weights ranged from 20 to 200 lbs. TNT, and the charge location is at the center of the DYSMAS models, and 12.7m (41.7 ft.) below the water surface (*i.e.* 0.1 m (3.9 in.) above the bottom of the water), as shown in Figure 4.

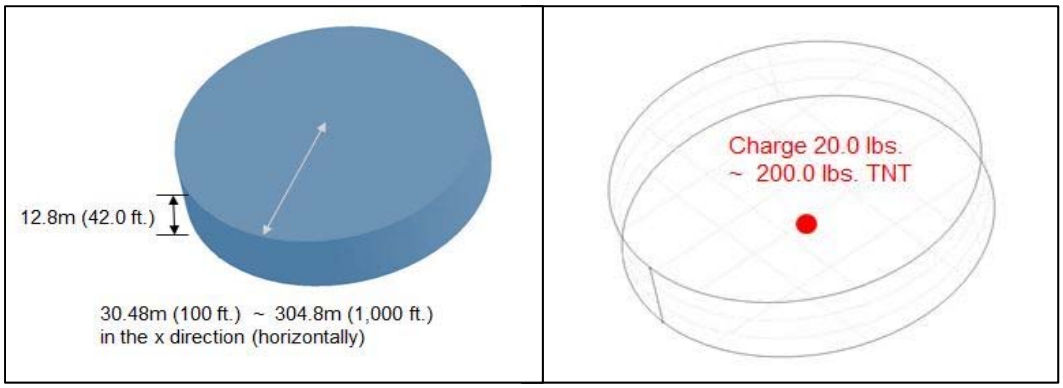


Figure 4: 3-D DYSMAS Baseline Model

The target parameters include the blast waveform (*i.e.* the pressure-time history), peak pressure, impulse intensity and energy flux density. Figure 5 presents the typical blast waveforms from 20 lbs. TNT UNDEX at the recording locations of 10 m (32.8 ft.) below the water surface and from 3.5 m (11.5 ft.) to 25 m (82.0 ft.) in the horizontal direction away from the charge, which are represented by the notations of (3.5m, 10m), (5m, 10m), (10m, 10m), (15m, 10m), (20m, 10m) and (25m, 10m) in Figure 5, respectively.

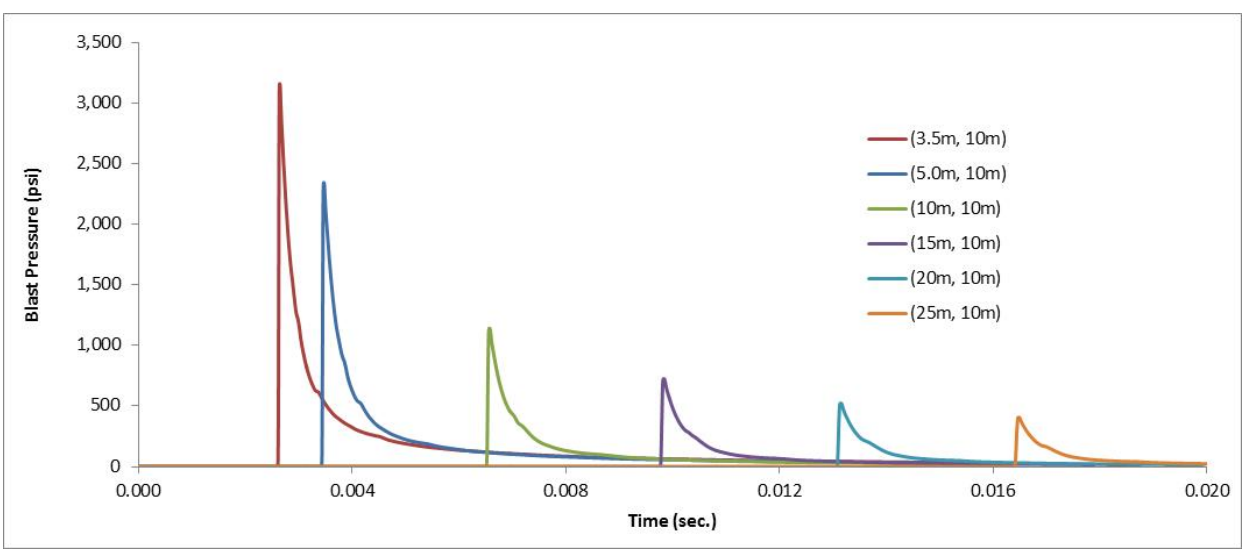


Figure 5: Typical Blast Waveforms from 20 lbs. TNT UNDEX

Figure 6 compares the waveforms from 20 lbs. with 200 lbs. TNT UNDEX at the two recording locations of (5m, 5m) and (10m, 10m) that are shown in Figure 7. The first location (5m, 5m) is 5m (16.4ft.) below the water surface and in the horizontal direction away from the charge, respectively, while the second one (10m, 10m) is 10m (32.8ft.) below the water surface and in the horizontal direction away from the charge, respectively.

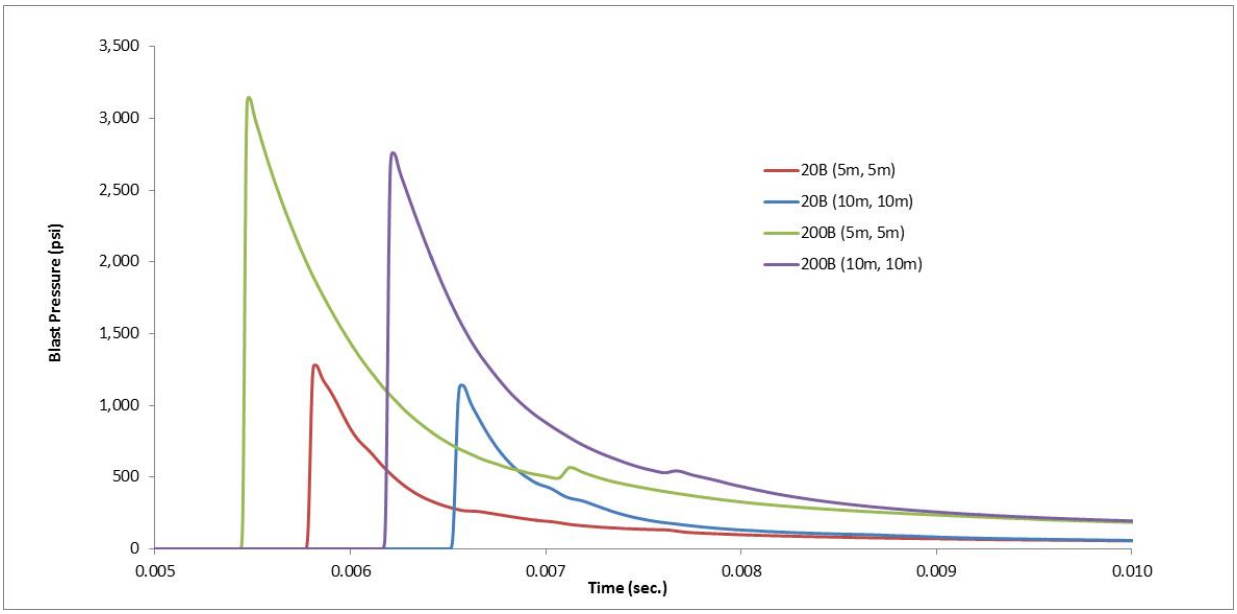


Figure 6: Waveforms from 20 and 200 lbs. TNT UNDEX at (5m, 5m) and (10m, 10m)

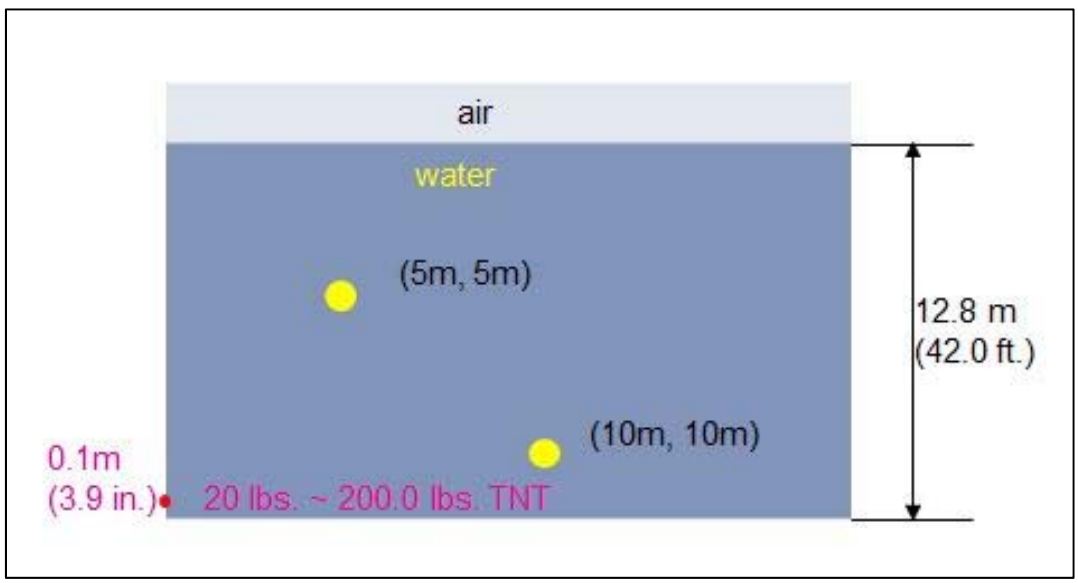


Figure 7: Two Recording Locations of (5m, 5m) and (10m, 10m)

The following equations (1) to (3) give the formulation for the peak pressure, impulse intensity and energy flux density, respectively:

Peak Pressure $$P_{max} = 52.1 \left(\frac{\sqrt[3]{W}}{R}\right)^{1.18}$$ Equation (1)

Impulse $$I_p = \int_0^t p(t)dt$$ Equation (2)

Energy Flux $$E_p = \frac{1}{\rho c}\int_0^t p(t)^2 dt$$ Equation (3)

where ρ ≈ 1,000 kg/m^3 (62.4 lbs. / ft^3) water density, and c ≈ 1,515 m/s. (4,970 ft./s) sonic speed in the water.

As shown in Figure 6, the relationship among P_{max}, NEW (W) and Distance (R) in Equation (1) can be easily confirmed.

5.2 Effects of Type I Mitigations from DYSMAS Simulations

The effects of Type I mitigations for 20 lbs. TNT UNDEX are presented in Figures 8 and 9, along with the baseline results at the two locations in Figure 7, respectively. As shown in Figures 8 and 9, Type I mitigations have little effects in UNDEX, although they are very effective in air blasts. This is because the blast wave propagation in water is completely different from that in air.

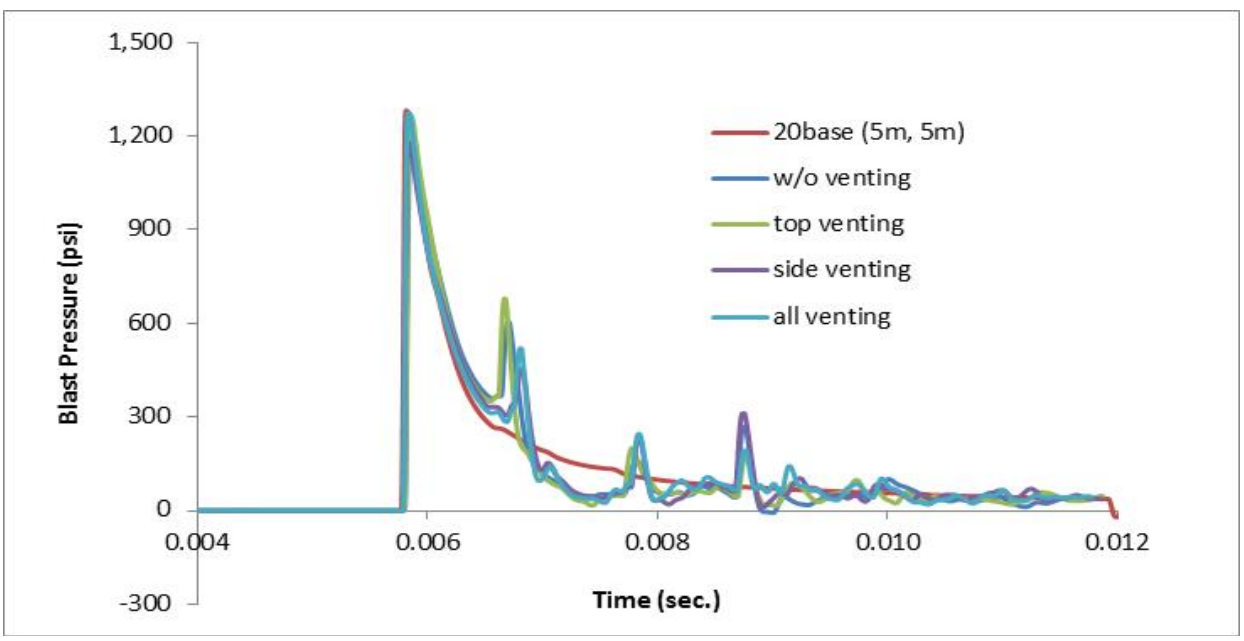


Figure 8: Effects of Type I Mitigations for 20 lbs. TNT UNDEX at (5m, 5m)

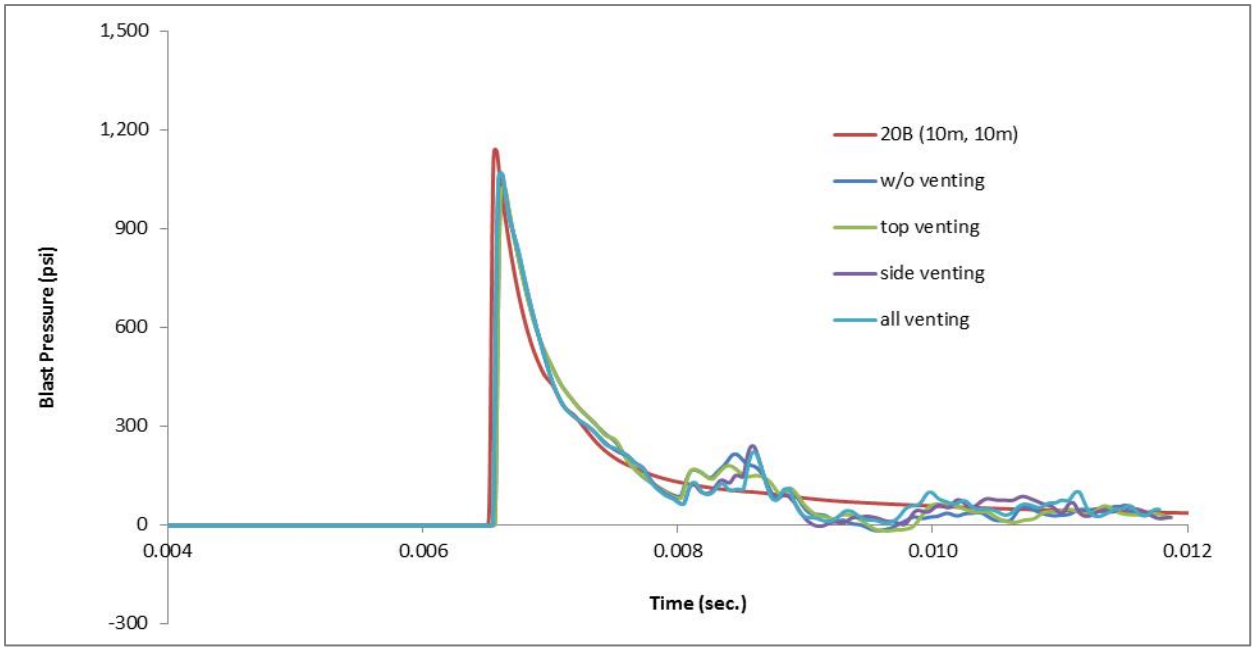


Figure 9: Effects of Type I Mitigations for 20 lbs. TNT UNDEX at (10m, 10m)

5.3 Effects of Type II Mitigations from DYSMAS Simulations

Figure 10 compares the effects of Type II mitigations for 20 lbs. TNT UNDEX with the baseline results at (5m, 5m). The double hull filled with sand or water has little effect in UNDEX, but the double hull filled with air gap may significantly reduce the blast pressure with time (*i.e.* the waveform).

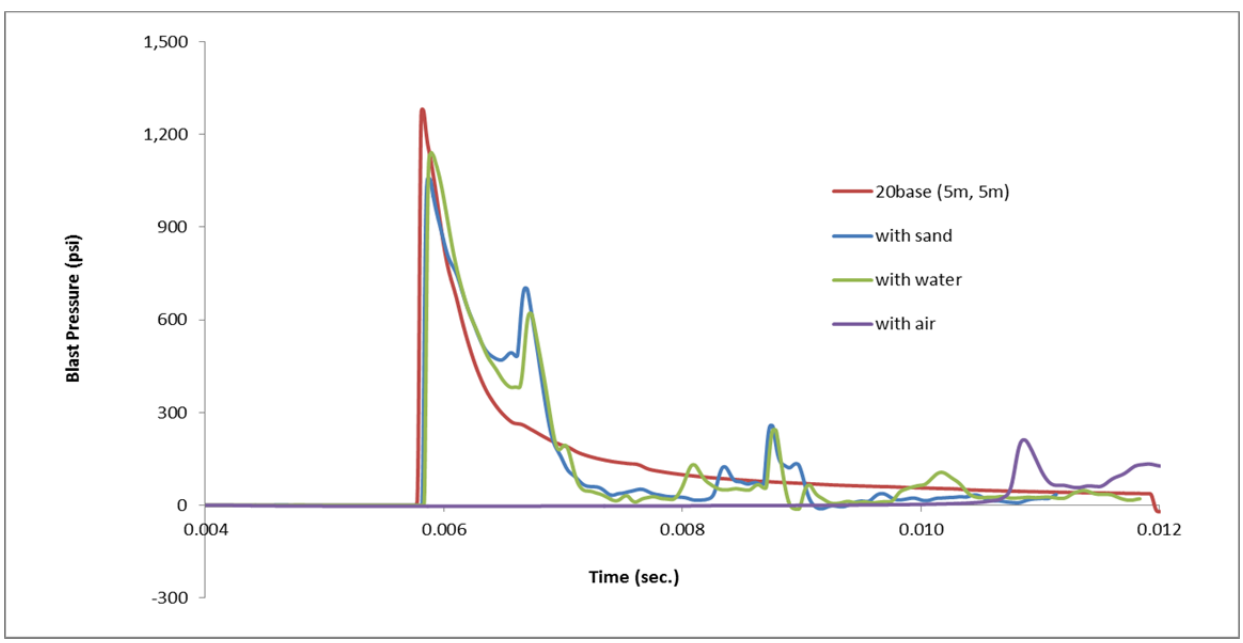


Figure 10: Effects of Type II Mitigations for 20 lbs. TNT UNDEX at (5m, 5m)

5.4 Effects of Type III Mitigations from DYSMAS Simulations

Figure 11 compares the effects of Type III mitigations with a 0.30 m (12 in.) air gap and a 0.61 m (24 in.) air gap for 200 lbs. TNT UNDEX at (10m, 10m), where only limited differences are observed (*i.e.* the red vs. green lines). The time delay in the green line for 0.61 m (24 in.) air gap is due to the fact that the blast waves propagate much slower in air (343 m/s, 1,125 ft./s) than in water (1,515 m/s, 4,970 ft./s).

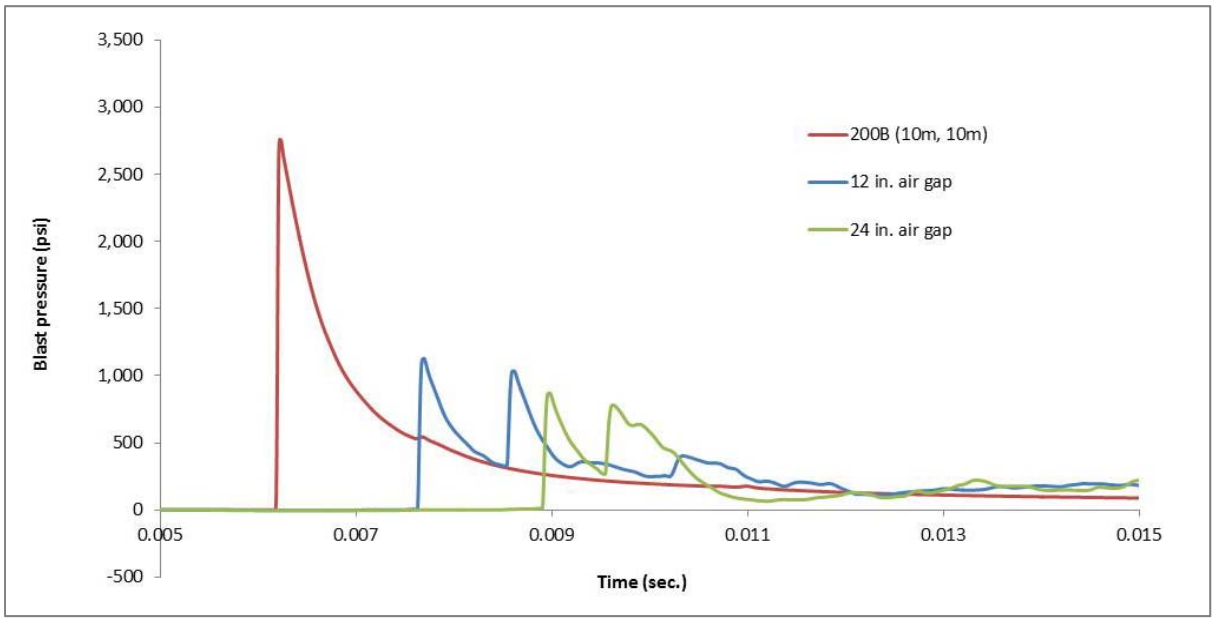


Figure 11: Effects of Type III Mitigations for 200 lbs. TNT UNDEX at (10m, 10m)

Figure 12 compares the effects of Type III mitigations for 20 lbs. TNT UNDEX with the baseline results at (5m, 5m). The tube filled with 50% air and water (*i.e.* the blue line) has little effects in UNDEX, but the tube filled with no less than 94% air (*i.e.* the green and purple lines) may significantly reduce the blast pressure with time (*i.e.* the waveform). This means the water in the tube must be less than a certain limit to reduce the blast waves in the surrounding water.

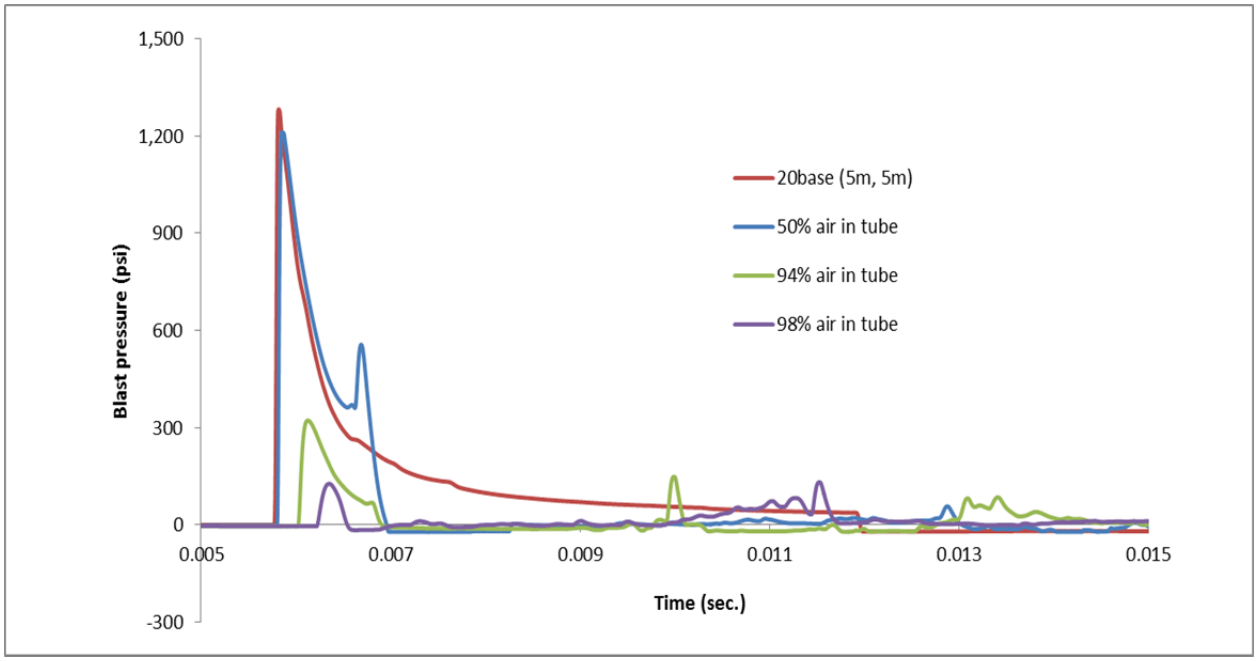


Figure 12: Effects of Type III Mitigations for 20 lbs. TNT UNDEX at (5m, 5m)

5.5 Effects of Type IV Mitigations from DYSMAS Simulations

Figure 13 shows the effects of Type IV mitigation for 200 lbs. TNT UNDEX at the recording location (5m, 5m). An air tank with 2.44 m (8.0 ft.) in diameter and at least 2.0 m (6.6 ft.) high may significantly reduce the blast pressure with time (*i.e.* waveform). Figure 14 compares the maximum blast pressures along the horizontal direction at 10m (32.8 ft.) deep from the water surface for the baseline scenario with those for the air tank with 2.44 m (8.0 ft.) in diameter under 20 lbs. TNT UNDEX. The corresponding impulses are compared in Figure 15. When the recording locations are closer to the charges, the effects of Type IV mitigation are more significant. The DYSMAS animations for Type IV mitigations indicated that air tanks with a certain volume and/or diameter changed the propagation paths of the blast waves so that the total blast energy was divided into smaller portions arriving at the target location at different time.

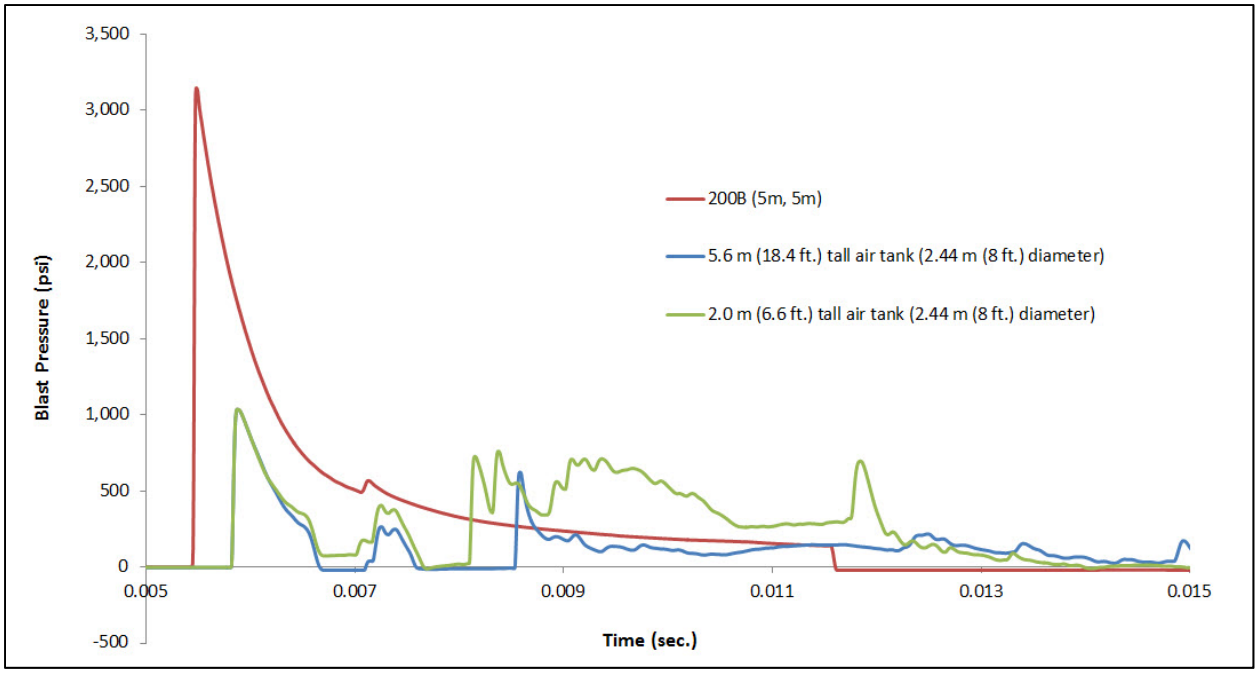


Figure 13: Effects of Type IV Mitigations for 200 lbs. TNT UNDEX at (5m, 5m)

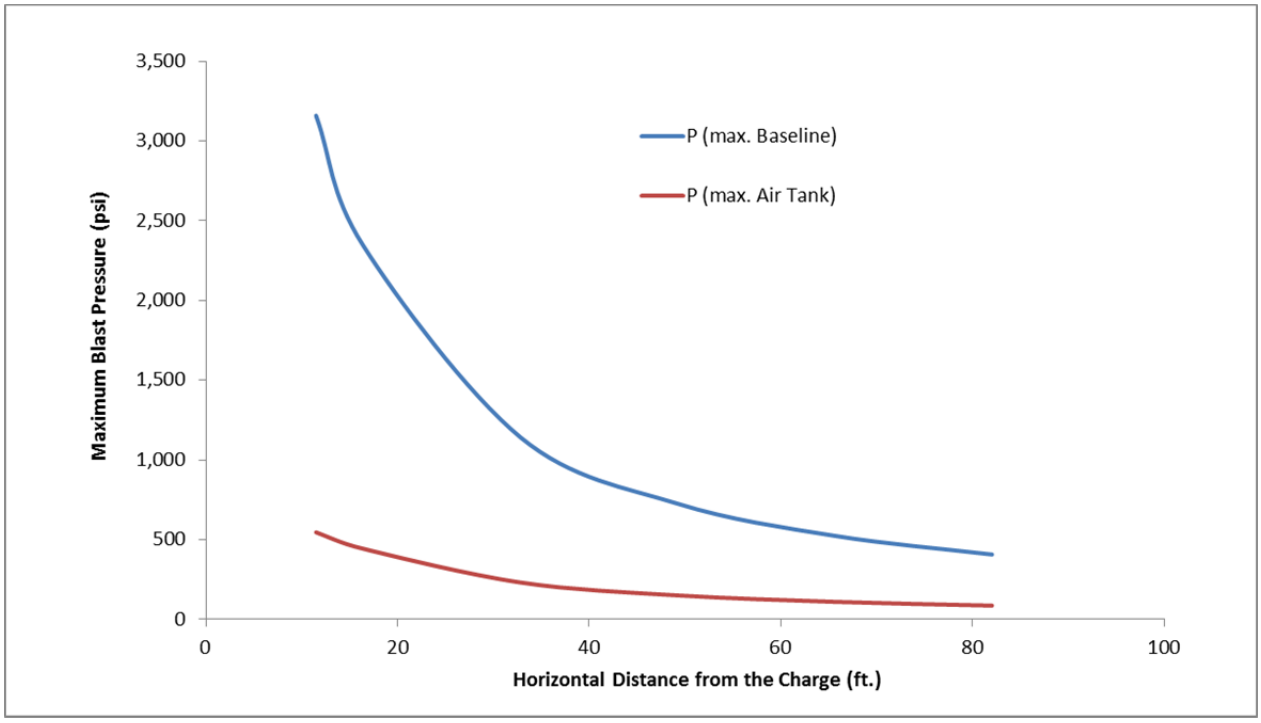


Figure 14: Effects of Type IV Mitigations on Maximum Blast Pressures (20 lbs. TNT)

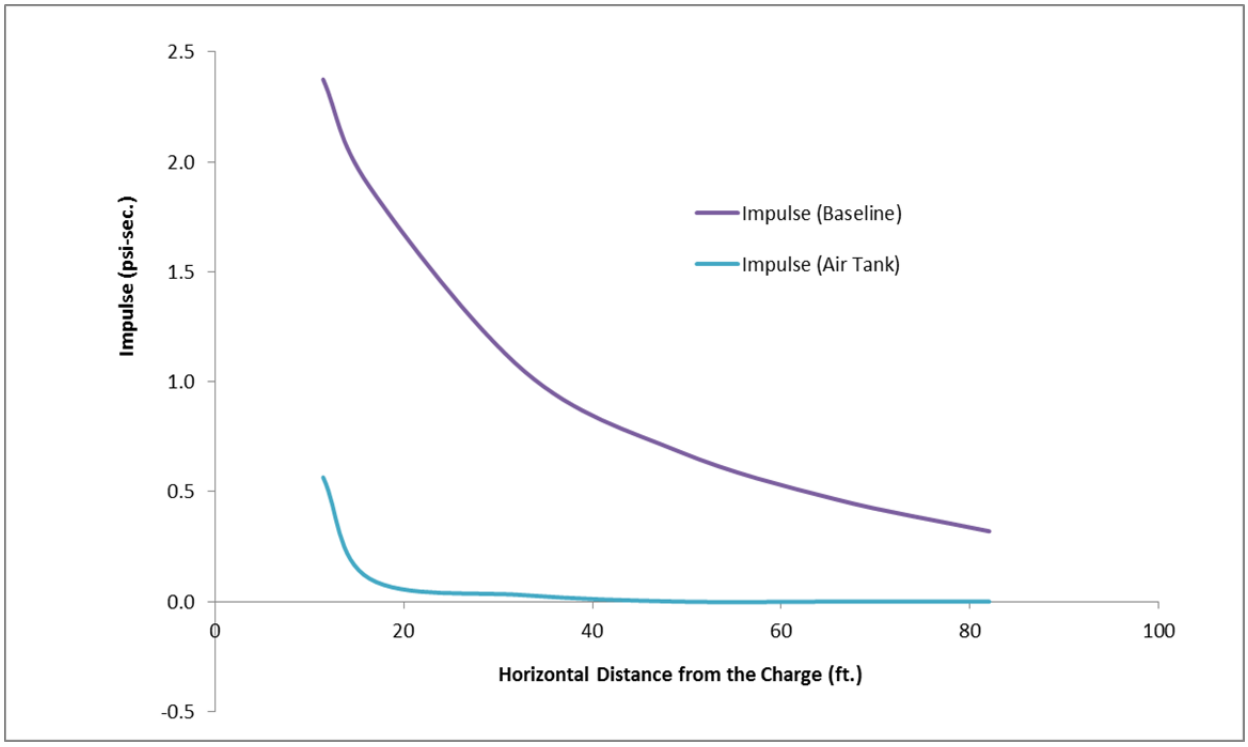


Figure 15: Effects of Type IV Mitigations on Blast Impulses (20 lbs. TNT)

DYSMAS simulations show that increasing the amount of air around the BIP could reduce the blast effects of the UNDEX. Table 2 summarizes the baseline scenario and the effects of the blast mitigations at (5m, 5m) from the DYSMAS simulations with both 20 and 200 lbs. of TNT. DYSMAS simulations were initially performed comparing various mitigation designs at 20 lbs. TNT for the four types of conceptual designs. The steel single hulls (Type I) were eliminated for further investigations because they did not work for UNDEX. DYSMAS simulations with 200 lbs. TNT were performed for the double hulls (Type II) filled with 24 inches thick air (instead of 12 inches thick air at 20 lbs. TNT) and for the air tank (Type IV) mitigation designs only, due to the limited fund and tight schedule of this R&D project. Thus, Table 2 contains "Not tested with 200 lbs. TNT" for Type II and III mitigation designs at 200 lbs. TNT. More DYSMAS simulations will be performed in the proposed Phase II of this project.

Table 2: Summary of Blast Mitigation Effects at (5m, 5m) from DYSMAS Simulations

Blast Effects Parameters	**Baseline**	**Double Hull (Type II) 0.3 m (12 in.) Air Gap**		**Tube Structure (Type III) with 94% Air inside Tube**		**Air Tank (Type IV) 2.44 m (8.0 ft.) Diameter**	
20 lbs. TNT							
Max. Pressure (psi)	1,282	212	83%	322	75%	149	88%
Impulse (psi-sec.)	0.84	0.42	50%	0.49	42%	0.53	37%
E (ft.-lbs. /in.2)	6.76	0.77	89%	0.52	92%	0.31	95%
200 lbs. TNT							
Max. Pressure (psi)	3,146	Not tested with 200 lbs. TNT		Not tested with 200 lbs. TNT		1,294	59%
Impulse (psi-sec.)	3.16					2.50	21%
E (ft.-lbs. /in.^{2})	58.6					17.6	70%

Of the four types of blast mitigation structures simulated, the air tank (Type IV) design is considered the best candidate for further development. This innovative design splits the total blast wave energy into multiple smaller amount of shock waves that arrive at the target location (*e.g.* 5m, 5m) at the different times, resulting in much lower blast peak pressures and impulses. In addition, the proposed air tank resists the shock waves directly coming from the bottom of the tank so that many options can be effectively utilized to ensure the safety of the air tank itself during BIP operations. The tube structure (Type III) is also shown to work very well at mitigating blast effects; however, this mitigation design is applicable in shallow water areas only, but is particularly useful for the BIP operation in the beaches or the surrounding areas of bridge piers, dry docks or other infrastructure facilities. The double hulls filled with air (Type II) are the modifications of traditional air bubble curtain mitigation designs. The literature review shows that the traditional air bubble curtains could survive during BIP operations up to 5.0 lbs. TNT only. DYSMAS simulations also show that the double hulls filled with air (Type II) were completely destroyed at 20 lbs. TNT. This was because the double hulls (Type II) had to resist the lateral blast pressure impacts. In general, the lateral resistance capacity of a structure (*e.g.* a double hull) is much less than the resistance capacity in the axial direction, as shown in the air tank (Type IV) mitigation design.

6.0 CONCLUSIONS AND IMPLICATIONS FOR FUTURE RESEARCH

The DYSMAS computer simulations showed that the caisson designs filled with air are effective at reducing blast effects. This "SEED" research project showed significant reductions in blast effects when Type IV and/or III caisson designs are applied. Therefore, the Phase II of this R&D project is proposed below.

Type IV caisson design is considered the best candidate for future development. More DYSMAS simulations should be performed to quantify a relation between charge size/location and air tank performance in the proposed Phase II of this R&D project. More simulations will be run with a much broader range of explosives and distances from the BIP to more precisely predict blast effects and capabilities of the caisson design before fabricating and testing a full scale caisson design with explosive blast ranging from 1 to 20lb equivalent to TNT. Upon further refinement of the Type IV design, a prototype will be built and tested in and under water environment with sensors to determine the reduction of blast effects.

7.0 LITERATURE CITED

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