Underwater Explosion Bubble Jetting Effects on Infrastructure

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Underwater explosions present a significant risk to structures because they were not designed for these types of loads and because water transmits explosive energy much more efficiently than air. The US Navy demonstrated that the effect of bubble jetting from an underwater explosion can result in significant late-time loading compared to the initial shock loading. However, neither the effects of bubble jetting on structures, where the explosion is likely to be lateral to the target rather than beneath it, nor the loading conditions required to produce bubble jetting effects on such structures (charge weight, submerged depth, and standoff distance to structure) are well understood. This investigation improves characterizations of bubble formation, collapse, and jetting near lateral targets. The research includes very small-scale tests to observe bubble jetting, slightly larger underwater blast experiments to determine bubble jetting loads on vertical structures, and larger-scale experiments to measure bubble jetting effects on the structural deformation to structures.

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Abstract

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Keywords: Underwater Explosion; Bubble Jetting; Finite Element; Structural Vulnerability; Small-Scale Experiments

Underwater Explosion Bubble Jetting Effects on Infrastructure

Introduction

Underwater explosions (UNDEX) present a significant risk of damage to structures. Because water transmits explosive energy much more efficiently than air, relatively small explosive charges detonated underwater may cause structures much more damage than those detonated in the air. Several realms of behavior exist during the process of an UNDEX, and while these will be described in detail, they can be summarized as the loading due to shock, bubble expansion, and bubble jetting. A bubble is generated underwater due to the inability of gaseous by-products of the UNDEX to vent into the air. Current engineering models able to accurately predict the shock environment and the bubble expansion loadings from underwater explosions could not, prior to this study, accurately predict the loading due to bubble jetting, should it occur. It was not well understood which loading conditions (charge weight, submerged depth, or standoff distance to a structure) resulted in bubble jet loading to structures. Most of these structures are vertical, so the bubble must jet horizontally. Using computer codes such as DYSMAS (McKeown, et. al, 2004), the Navy demonstrated that bubble jet loading can result in significant late-time loading (compared to the shock loading) for vertical structures. The bubble jet loading can potentially impart as much impulse as the initial shock loading, although its force is concentrated on a smaller surface area.

A major weakness of the computational models was the lack of validation or even calibration against experimental data to confirm or correct the calculated development of the loads and the damage effects from bubble jetting. These data were very limited prior to this study. The Navy conducted large-scale tests against ship hulls, but limited data were found for bubble jetting onto vertical surfaces. This study by the US Army Engineer Research and

Development Center (ERDC) specifically addresses this shortcoming. Significant effort was placed on gathering experimental data at several scales for validation of high-fidelity computational models and providing anchoring points for the development of fast-running engineering-level models.

Problem Statement

Several questions needed to be answered to address the determination of the bubble jet loading on structures and the consequences of those loads: (1) Under what conditions will a bubble impart a jet on a structure? (2) What is the total force imparted by the bubble jet on the structure, and (3) What is the structural response to the bubble jet loading? Some conditions help to constrain the parameter space of this problem. First is an upper constraint on the size of the charge; this is dependent on the vulnerability of the target. If the charge size is sufficiently large so that the shock loading causes loading above some damage level, the bubble jet loading is inconsequential no matter how large it is. Further, the relative shallowness of the water level (as opposed to open deep water conditions) also reduces the charge size of concern for bubble jet loading because a large enough bubble will vent to the surface (or jet toward another surface on which it interacts) rather than jet to the structure of interest.

Approach and Experiments

A systematic approach to this problem and a combination of experimental and numerical work were employed at several scales to address these questions. Three main scales were used: a very small scale using Spark Gap tests, a slightly larger scale in the Naval Special Weapons Center (NSWC)/Carderock (NSWCCD) Test Pond, the Mid-Scale Test Series (MSTS) at ERDC, and the still larger Big Black Test Series (BBTS) at ERDC.

This combination of experiments and numerical simulations was used to provide the necessary results to answer the questions of interest. The very small scale was used to study the phenomenology of the bubble jet, i.e., determine under what conditions the jetting would strike the structure. Larger tests (at Carderock and the MSTS) measured the loads generated by the bubble jet against rigid and flexible targets. Finally, structural response to the bubble jet was measured in the BBTS experiments. Each of these test series had supporting numerical simulations to determine the required charge size and location to get the desired response. The Spark Gap test results were used to develop a simplified "engineering rule" that could generally approximate the bubble jet and the corresponding loads very quickly. This rule can be easily used by a PC-based vulnerability code to assess damage from an UNDEX.

Although different information was captured from each test series, the general approach was to detonate at a predetermined underwater location an explosive charge that would generate a bubble that would jet and strike the target. When possible, high-speed video of the bubble behavior recorded the jet behavior, including the size of the jet and the timing of the bubble process. Pressure was recorded in several ways, including free-field water-shock measurements and target surface measurements. Reaction structures were built for most all the scales of testing, including one as simple as a vertical plate for the Spark Gap tests, up to a large reinforced-concrete structure to support the target in the BBTS tests. The objective in all tests was to provide a vertically placed target for the bubble jet to strike. The rigidity of the target depended on the test series and its intent. Some tests necessitated a fixed rigid target (at least as fixed and rigid as possible under the explosive loading conditions), while others included a flexible target to record the ensuing motion as the structure was loaded by the UNDEX.

Table 1 shows a summary of the testing series and the information captured for each. This includes whether visuals were recorded for the bubble, whether the test was considered “scaled,” whether pressure or loading information was captured, and whether a flexible structural response was part of the test series. The progression from the top of the table to the bottom moves through the three major parts of the bubble jet study: bubble jet definition, loading from the bubble jet, and structural response to the jet.

Table 1: Test series information.

Test Series	Bubble Dynamics (Visual)	Scaled	Pressure Data	Structural Response
Spark Bubble Tests	✓	**Yes**	**No**	**No**
NSWCCD Pond UNDEX Tests	✓	**No**	✓	**No**
ERDC MSTS	✓	**No**	**No**	✓
ERDC Pond UNDEX Tests	**No**	**No**	✓	✓

The Spark Gap test is a process by which electrical energy is converted into a low volume of plasma, which has temperatures as high as 20,000 degrees K and pressures as high as 10,000 atmospheres (Chahine and Kalumuck, 1998). Because of the high pressures, the liquid near the plasma interface is initially compressed. This high pressure leads to the formation of a shock wave that radiates outward. The energy in the shock wave comprises 20 to 50 percent of the energy imparted by the spark into the water (Chahine and Kalumuck, 1998), similar to UNDEX dynamics. After emission of the shock wave, the pressure in the gas sphere quickly decreases but remains well above that of the surrounding liquid. The pressurized gas expands into a large bubble that subsequently collapses and re-expands. The radius versus time of the bubble was shown in many studies conducted by DynaFlow, Inc. for the Navy to follow the same dynamic behavior as an UNDEX bubble. The application of the spark-generated bubble facility to the

UNDEX jetting problem is based on the fact that we can easily conserve all geometric scales in the spark chamber while enabling excellent flow visualization. The Froude number – essential for scaling the bubble behavior - can also be conserved simultaneously by reducing the pressure above the free surface.

Spark-generated bubbles are strong candidates for laboratory-scale models of UNDEX bubble dynamics and are, therefore, excellent sources of data for validation of high-fidelity numerical simulations. Their relative safety, cleanliness, and compactness enable high-quality observations of bubble dynamics at relatively low cost compared to experiments involving explosives. High-speed cameras photograph the spark-generated bubbles and provide high-quality observations of bubble dynamics including clear visualization of reentrant jet formation inside the bubble.

While small-scale UNDEX experiments can be designed to match the main geometric parameters, it is much more difficult to match the Froude parameters. For example, in the full-scale UNDEX structure-interaction problem, the Froude numbers can vary from approximately 2 to 30. In the planned NSWCCD tests, the Froude numbers range from 30 to 60, while in the ERDC tests, the range is 10 to 15. The spark-generated bubbles can match most of the above ranges and will enable testing, evaluation, and comparisons between the different cases.

The MSTS was contained in a free-standing reinforced concrete structure approximately 40 ft (12.2 m) by 11 ft (3.4 m) by 6 ft (1.8 m) with a steel reaction structure holding a target plate that was alternated between a thin responding steel sheet and a much stiffer “non-responding” plate with stiffeners. High-speed video and the acceleration of the plate were recorded so correlation could be made between the behaviors of the bubble from expansion through jetting to the response of the steel target plate. Multiple charge sizes and standoffs were tested to obtain validation data for the numerical codes. A larger reinforced concrete reaction structure was constructed within an open pond for the BBTS to record the response of a 10-ft-(3.3-m) square steel target. The target was constructed to approximate a scaled stiffened plate. The limitations on the scaling of the bubble within the constraints of the basin meant that the tests were not truly "scaled." Water-shock pressures were recorded on the target face and within the open water (free field). Accelerations and strains were recorded on the structure itself. High-speed video captured the structural response, but the water was not sufficiently clear to capture the bubble behavior.

Computational support was provided for each of the test series to first scope the charge sizes and locations necessary to generate the desired response and then, once calibrated and validated against experimental results, to provide numerical results for scenarios that were not tested. As typically occurs in this type of combined numerical and experimental program, simulations provided invaluable insight before the tests and then could expand on the information gained after the test was performed. Data were gathered at discrete and limited locations during the tests, usually due to limitations on instrumentation and/or funding, while information could be gleaned from the simulation at almost any point in the domains with little extra cost or effort.

Several numerical codes were used to model the UNDEX at the various scales used throughout this investigation. DYSMAS was used to model experiments at all the scales larger than the Spark Gap tests, as it has the ability to simulate the entire UNDEX, including all parts of its process from generation of the shock to bubble jetting to the response of the structure. The motion of the bubble from initiation through expansion, collapse, and jetting until the jet is about to strike the opposite side of the bubble can be captured very well with the Boundary Element Method (BEM) code 3DynaFS (Chahine and Kalumuck, 1998). This code can numerically simulate bubble behavior orders of magnitude faster than DYSMAS partially due to the nature of the BEM and the ability of the code to treat the water as an incompressible fluid, which enables several approximations to be used. This method still accurately captures the bubble behavior under those assumptions and approximations.

BEM can describe the bubble shape and the surrounding pressure field as it changes through time. This method applies to this problem when the fluid flow can be assumed to be a potential, and heat and mass transfer at the boundaries is negligible. 3DynaFS solves the fluid-flow problem when the liquid can be modeled as incompressible and the flow is not rotational. Development of 3DynaFS and its application to the UNDEX bubble problem are described in Chahine and Duraiswami (1994) and Chahine, Duraiswami, and Kalumuck (1996). These reports provide considerable information on the behavior of bubbles in open water and near-free surfaces, solid objects, and moving structures and include fluid-structure interaction (FSI) effects. 3DynaFS is fast, very efficient, and very effective in modeling UNDEX and solving cavitation bubble dynamics problems. DYSMAS is a coupled code that was developed by NSWC/Indian Head and the German government to calculate UNDEX environments and the ensuing marine vessel's response during a single-coupled calculation incorporating fluid-structure interaction. It is based on the use of three modules: an Eulerian code to perform the fluid flow calculation, a Lagrangian code to perform the structural response calculation, and a coupler module that interfaces information between the two other codes. This combination enables DYSMAS to execute simulations that include explicit shock fronts, bubble jets, structural fracture, and fluid breakthrough. Included in DYSMAS are the capabilities to handle compressible and incompressible fluids. The coupled code DYSMAS was developed to calculate scenarios in which the range from detonation to structure is anywhere from in contact to far field.

Very good experimental data were captured in each of the test series, allowing comparisons to be made between experimental and numerical results. A comparison at a moment in time between a Spark Gap Test and a BEM simulation is shown in Figure 1, which shows good correlation between the actual and the simulated bubbles.

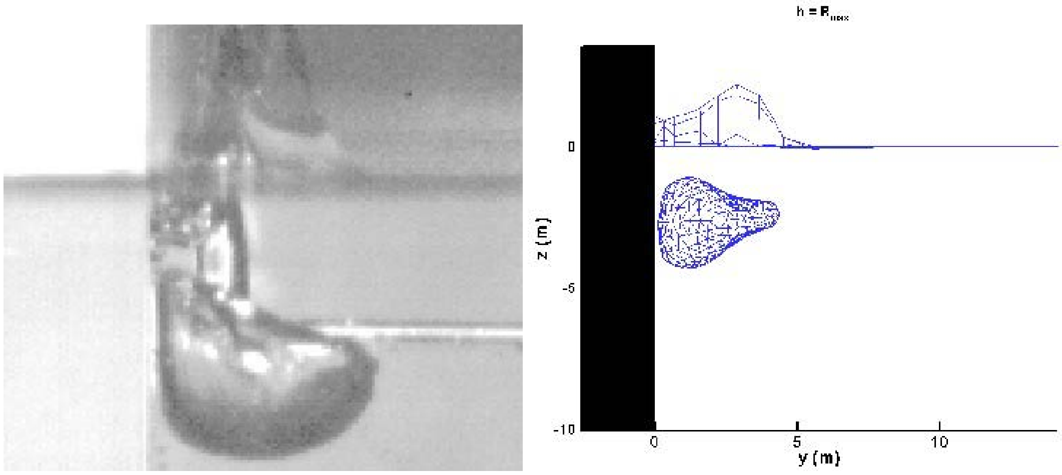

Figure 1: Experimental Spark Gap test (left) and BEM simulation (right) of bubble jet against a target.

Similar video quality was seen in the LWTS shown in Figure 2. This shows two experimental views of the bubble behavior, covering both the initiation of jetting and the point of contact of the jet with the target. Figure 3 shows a numerical result from DYSMAS for one of the BBTS tests as the bubble is about to collapse toward the target. Shown are the Lagrangian structure and a slice of density at the centerline within the Eulerian fluid domain. The extent of the bubble is seen in blue at mid-height of the structure. Distribution of this paper prevents the inclusion of detailed results, so only these general descriptions of the process are provided.

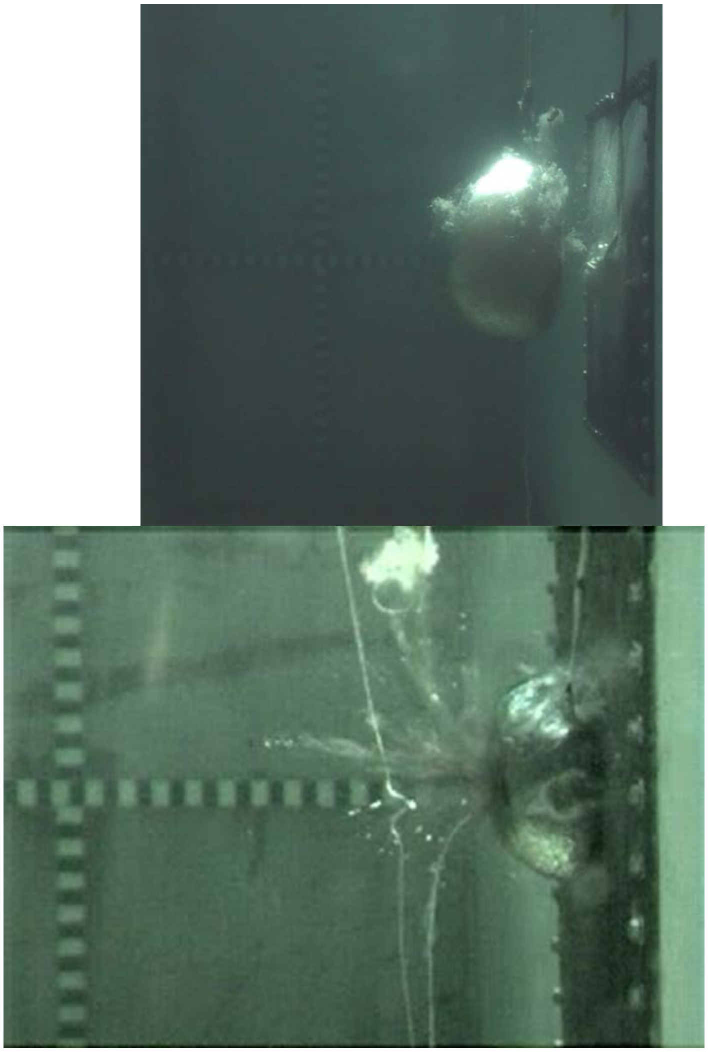

Figure 2: Snapshots from LWTS of initiation of bubble collapse and the moment of jet contact with the target.

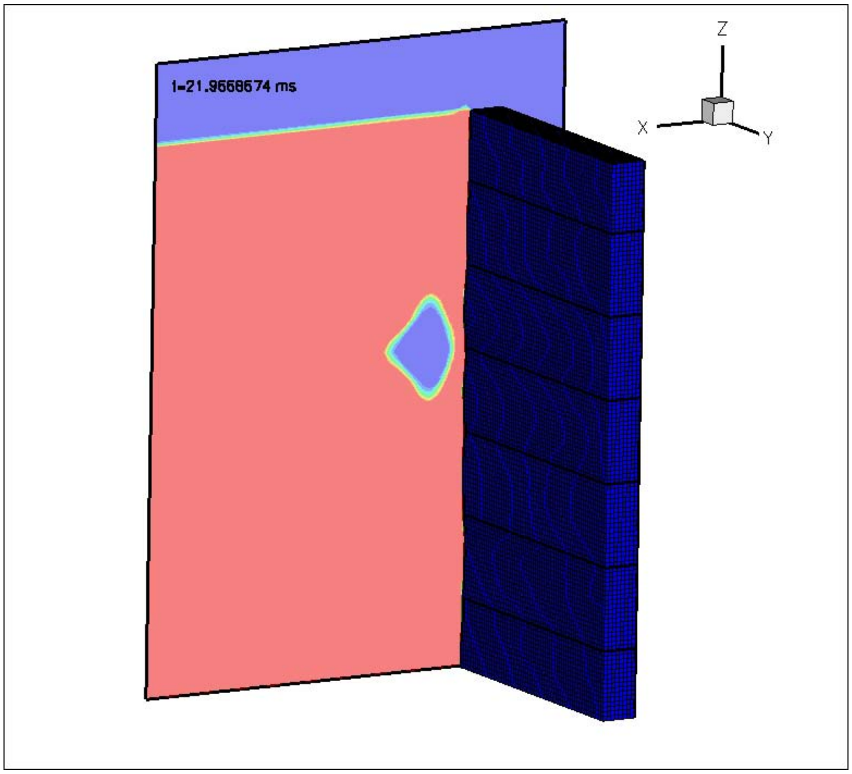

Figure 3: DYSMAS calculation of a BBTS experiment with bubble about to collapse toward target.

This combination of experimentation and computational work will result in the answers to the original questions in the problem statement. Paraphrased: When is bubble jetting a concern? What will the loading be from a bubble jet? What is the structural response to the bubble jetting loads? By validating the numerical simulations against precision small-scale UNDEX experiments, a large amount of confidence is generated in the ability of the numerical codes to simulate the full-scale problem scenarios. Once the resulting loading and behavior caused by bubble jetting is determined, mitigation schemes will be analyzed as to their effectiveness in reducing the loading and/or response of the structure.

End Users/Customers/Who would benefit

Any structure that is exposed to water is at risk from an UNDEX attack. This research quantifies the non-shock portion of the UNDEX loading (the shock portion of the loading is well characterized and simplified models were previously developed), and develops simplified methods that will be used in vulnerability engineering-level codes to quickly provide approximate answers to owners and analysts as to the vulnerability of the structure of concern to UNDEX attacks.

Summary

An extensive set of experiments and numerical simulations were conducted to define bubble jetting behavior, the loads generated on vertical structures, and the resulting structural responses. A considerable amount of work remains to transfer these results from the idealized structures used in the experiments to the kinds and levels of responses that can be expected/predicted in actual structures. Characteristics of the bubble jet were studied, and some simplified methods were developed to facilitate the predictions of these scenarios without the need for complicated and time-consuming high-fidelity numerical simulations. While these predictions will be very simplified, the intent is to capture a conservative estimate of the loading and response of water-sided targets, including all phases of the loading from shock through possible bubble jet behaviors, to UNDEX.

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