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COMPUTER SIMULATION OF UNDERWATER NUCLEAR EVENTS

Minao Kamegai

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Minao Kamegai

ABSTRACT

This report describes the computer simulation of two underwater nuclear explosions, Operation Wigwam and a modern hypothetical explosion of greater yield. The computer simulations were done in spherical geometry with the LASNEX computer code. Comparison of the LASNEX calculation with Snay's analytical results and the Wigwam measurements shows that agreement in the shock pressure versus range in water is better than 5%. The results of the calculations are also consistent with the cube root scaling law for an underwater blast wave. The time constant of the wave front was determined from the wave profiles taken at several points. The LASNEX time-constant calculation and Snay's theoretical results agree to within 20%. A time-constant-versus-range relation empirically fitted by Snay is valid only within a limited range at low pressures, whereas a time-constant formula based on Sedov's similarity solution holds at very high pressures. This leaves the intermediate pressure range with neither an empirical nor a theoretical formula for the time constant. These one-dimensional simulations demonstrate applicability of the computer code to investigations of this nature, and justify the use of this technique for more complex two-dimensional problems, namely, surface effects on underwater nuclear explosions.

INTRODUCTION

The physics of an underwater shock wave driven by a nuclear explosion is complex, and often exact solutions are not available. Applying a well developed hydrodynamic code can greatly facilitate computation, and can result in a much better understanding of the problem. We simulated underwater nuclear effects with the LASNEX code to study propagation and attenuation of

shock waves in water. The simulations were confined to spherical geometry, which is appropriate for explosions in infinite media.

The main objective of this work was to show that our computer code, LASNEX, could be used to study underwater shock propagation down to the very weak shock regime, i.e., overpressures of the order of 0.1 GPa. Therefore, it is appropriate first to show that this can be done for one-dimensional (1-D) problems before attempting more complex two-dimensional (2-D) ones involving interactions at the sea surface. This report summarizes our 1-D calculations.

First we computed an old U.S. Pacific test, Operation Wigwam, which was a deep underwater explosion. Then the same method was applied to simulate a hypothetical explosion of greater yield. The results were studied in light of Snay's theoretical work. In the end, we will demonstrate the credibility of computer simulation for underwater nuclear explosions and thus justify extending this technique to study more complex 2-D problems.

COMPUTATION

SIMULATION I - WIGWAM

Operation Wigwam¹⁻³ was a deep underwater test in the Pacific. The shot was a primitive device that was placed at a depth of 2,000 ft, where the ocean depth was 15,000 ft.

The entire computation was carried out with LASNEX, which is a Lagrangian code developed for laser fusion research.^{4,5} The computation starts with detonation of the device, which generates a strong shock wave (0.3 TPa). The wave then propagates out to about $0.27 \text{ km}/(\text{kt})^{1/3}$ for more than $140 \text{ ms}/(\text{kt})^{1/3}$, during which the peak pressure decays to 15 MPa. The simulation is spherical and one-dimensional, that is, it represents a sphere of water with an energy source placed in the center. The weapons effects model included the mass and the characteristics of the materials present in the energy source. A description of the source has been given elsewhere.⁶

With the limited number of zones available, a fine zoning (20 ~ 30 cm/zone) could be maintained only at the wave front. The computation was periodically stopped, and the grid lines behind the wave front were transferred to the front of the wave without perturbing the shock front.

Since LASNEX is a Lagrangian code, numerical integrations are done with the minimum truncation error. Combined with a well developed equation of state of water,⁷ the LASNEX calculation demonstrates remarkable stability and accuracy. Figure 1 shows an example of a wave profile at $147 \text{ ms}/(\text{kt})^{1/3}$ after explosion. The wave front is at $244 \text{ m}/(\text{kt})^{1/3}$ from the center of explosion, and the peak pressure is a mere 14.4 MPa. Yet, the profile shows no sign of numerical instability.

The pressure and range of the shock wave were scaled to that for a 1 kt explosion by dividing the range by the cube root of the yield expressed in kt. The data are given in Table 1 and plotted in Fig. 2.

The time constant is an important parameter because the damage to underwater objects is induced by the total impulse delivered by the wave rather than the strength of the peak pressure. The time constant was determined from the wave profiles taken at several points by measuring the slope of the wave profile plotted in a semilog scale. Figures 3 and 4 give examples of the weak shock and the strong shock, respectively. The weak 0.26-GPa shock (Fig. 3) is almost a perfect exponential function whereas the strong 31-GPa shock (Fig. 4) deviates from the exponential pattern. Nevertheless, we assigned a time constant to the strong shock by measuring the slope of a tangent drawn at the peak. The time constant and range, scaled to 1 kt by dividing each by the cube root of the yield expressed in kt, are given in Table 2. All of the data are plotted in Fig. 5.

SIMULATION II

A hypothetical modern device with a greater yield would generate more radiation than the earlier device. Our simulation of this hypothetical device has been described elsewhere.⁶ In the initial phase where the emission of energetic x rays is a dominant process, a transport calculation was done until 97% of the yield was deposited in the surrounding medium. At this point, the computational mode was switched to a diffusion calculation, and the computation continued with the energy source slightly modified by deletion of some grid lines. The error introduced in this transition is estimated to be less than 2%. The calculation was carried out to $0.27 \text{ s}/(\text{kt})^{1/3}$ while the wave propagated $0.51 \text{ km}/(\text{kt})^{1/3}$, the pressure decaying to 12 MPa. The accuracy and stability of the LASNEX calculation are very evident in the wave

Fig. 1. Simulation I wave at $14.7 \text{ ms}/(\text{kt})^{1/3}$.

profile shown in Fig. 6. The pressure-versus-range data, scaled to 1 kt, are given in Table 1 and plotted in Fig. 2.

Once again, the time constant was determined at several points. Figures 7 and 8 are examples of the wave profile from which the time constant was determined. The strong 0.28-TPa shock (Fig. 7) does not decay exponentially whereas the weak 21.1-MPa shock (Fig. 8) shows an almost perfect exponential pattern. The time constant and range, scaled to 1 kt, are given in Table 2 and Fig. 5.

RESULTS AND DISCUSSION

Underwater explosions have been studied by many investigators.^{8,9} Snay,¹⁰ in particular, has extensively studied the phenomena of nuclear explosions in water. His calculations treated a point source explosion, i.e., the instantaneous release of energy by an infinitely small explosive. Furthermore, the initial radiative phase was entirely omitted, and the yield of the nuclear explosion was treated only as a hydrodynamic energy.

Table 1. Range (R) vs pressure (p).

Simulation I		Simulation II	
R[m/(kt) ^{1/3}]	p(GPa)	R[m/(kt) ^{1/3}]	p(GPa)
1.30	353.	1.45	279.
1.43	276.	1.73	179.
1.92	136.	1.94	126.
2.98	49.3	2.16	96.1
3.95	22.1	2.94	44.7
4.78	19.3	4.05	19.4
5.50	9.72	4.91	11.4
6.15	7.72	6.31	6.27
6.73	6.33	8.97	2.71
7.29	4.88	12.9	1.05
7.79	4.40	19.4	0.507
8.69	3.18	20.0	0.480
9.59	2.39	25.2	0.322
10.3	2.00	30.6	0.237
11.1	1.70	35.9	0.189
11.7	1.36	60.8	0.0855
12.4	1.20	62.5	0.0822
13.7	0.973	76.9	0.0620
15.8	0.779	84.6	0.0543
18.7	0.601	96.4	0.0453
21.4	0.467	108.	0.0394
24.1	0.376	127.	0.0321
27.2	0.315	131.	0.0309
29.1	0.278	154.	0.0253
29.5	0.267	166.	0.0231
34.1	0.217	171.	0.0220
38.7	0.174	177.	0.0209
43.5	0.147	196.	0.0184

Table 1. Continued.

Simulation I		Simulation II	
$R[m/(kt)^{1/3}]$	$p(\text{GPa})$	$R[m/(kt)^{1/3}]$	$p(\text{GPa})$
48.0	0.128	210.	0.0168
52.5	0.111	217.	0.0162
57.0	0.0993	258.	0.0131
61.5	0.0896	278.	0.0120
66.0	0.0805		
70.4	0.0743		
74.8	0.0683		
79.1	0.0631		
83.5	0.0585		
87.7	0.0542		
92.1	0.0508		
98.5	0.0461		
128.	0.0318		
130.	0.0311		
160.	0.0241		
181.	0.0206		
217.	0.0167		
275.	0.0124		

Table 1. Continued.

Snay's theory		Wigwam	
$R[m/(kt)^{1/3}]$	$p(\text{GPa})$	$R[m/(kt)^{1/3}]$	$p(\text{GPa})$
1.32	381.4	16.0	0.626
2.34	72.67	20.6	0.374
2.96	37.73	76.5	0.0579
4.55	12.50	96.3	0.0446
5.34	8.143	171.	0.0233
7.92	3.199		
10.3	1.800		
17.0	0.6589		
22.7	0.3911		
48.5	0.1248		
132.	0.0342		
187.	0.0225		
342.	0.0111		

Table 2. Time constant vs range.

Simulation I		Simulation II		Snay's Theory	
R	θ	R	θ	R	θ
$\left[\frac{m}{(kt)^{1/3}} \right]$	$\left[\frac{ms}{(kt)^{1/3}} \right]$	$\left[\frac{m}{(kt)^{1/3}} \right]$	$\left[\frac{ms}{(kt)^{1/3}} \right]$	$\left[\frac{m}{(kt)^{1/3}} \right]$	$\left[\frac{ms}{(kt)^{1/3}} \right]$
1.44	0.0135	1.45	0.0157	1.89	0.0152
2.54	0.0427	2.15	0.0429	2.96	0.0363
3.46	0.109	7.01	0.500	4.55	0.155
4.63	0.188	18.8	2.29	7.92	0.528
5.74	0.342	96.5	8.10	14.8	1.66
6.94	0.438	176.	10.4	48.5	6.02
8.74	0.731	276.	11.5	85.9	8.17
10.5	1.14			132.	9.56
12.5	1.39			187.	10.7
15.2	1.70			342.	12.7
19.1	2.40				
24.4	2.77				
29.7	4.03				
100.	9.06				
217.	11.1

Fig. 2. Pressure vs range.

Fig. 3. Wave profiles at $29.6 \text{ m}/(kt)^{1/3}$.

Fig. 4. Wave profile at $3.45 \text{ m}/(kt)^{1/3}$.

Fig. 5. Time constant vs range.

Fig. 6. Simulation II wave at $0.170 \text{ s}/(\text{kt})^{1/3}$.

Fig. 7. Wave profile at $1.45 \text{ m}/(\text{kt})^{1/3}$.

Fig. 8. Wave profile at $0.176 \text{ km}/(\text{kt})^{1/3}$.

In Snay's analysis, the propagation of shock driven by a nuclear explosion was divided into three phases: the high-pressure region (greater than 3.2 GPa), the intermediate region (3.2 GPa to 22 MPa), and the low-pressure region (less than 22 MPa). A pressure-distance relation for the wave was obtained assuming that the total energy of the spherical disturbance caused by the explosion remains constant and equal to the hydrodynamic yield, Y , of the weapon. The shock parameters were obtained by integrating the hydrodynamic equations.

In the high-pressure region, the similarity solution^{11,12} was applied whereas in the low-pressure region an empirical relation¹³ for pressure region where rigorous solutions are not available, a greatly involved iteration method was used.¹⁰ The method, which was developed by Snay and Matthias,¹⁴ interrelates the peak pressure, time constant, and wave profile as characterized by the shape factor at the wave front,

$$f = \left[\frac{P(\partial^2 P / \partial t^2)}{(\partial P / \partial t)^2} \right]_{r=r_1} . \quad (1)$$

Clearly, the shape factor is unity for an exponential wave and zero for a square or triangular wave. This means that the Snay and Matthias theory requires an a priori assumption of the wave profile. The shape factor can be determined exactly in the high-pressure and low-pressure regions; then, in the intermediate region the shape factor may be interpolated. By this method, Snay et. al.¹⁰ were able to calculate the shock parameters in the intermediate region.

The pressure-versus-range data calculated by Snay are given in Table 1 and plotted in Fig. 2. Also shown in the table and figure for comparison are five data points taken from the Wigwam measurements.^{3,4} Although the error bars were not given for these points in the Wigwam-measurement reports, the instrumentation error was estimated to be about 20%. In addition to his theoretical calculation, Snay obtained an empirical fit for low pressures,¹⁵

$$P(\text{GPa}) = 7.889 \left\{ R[m/(kt)]^{1/3} \right\}^{-1.13} \quad (2)$$

For high pressures, Chernyi's approximation to Sedov's similarity solution^{11,16} gives

$$P(\text{GPa}) = 388.3 \left\{ R[m/(kt)]^{1/3} \right\}^{-2} \quad (3)$$

These formulas are plotted for comparison in Fig. 2.

Similar data for time constant versus range from Snay's calculation are given in Table 2 and plotted in Fig. 5. Snay also empirically fitted the time-constant-versus-range data in the low-pressure region¹⁵ (large time constants):

$$\theta[ms/(kt)]^{1/3} = 2.953 \left\{ R[m/(kt)]^{1/3} \right\}^{0.22} \quad (4)$$

In the high-pressure region, Chernyi's approximation to Sedov's similarity solution^{11,16} gives (small time constants)

$$\theta[ms/(kt)]^{1/3} = 3.770 \times 10^{-3} \left\{ R[m/(kt)]^{1/3} \right\}^{5/2} \quad (5)$$

These formulas are plotted for comparison in Fig. 8.

Most of the computer-generated data points in Table 1 are plotted in Fig. 2. In the intermediate- and low-pressure regions, the LASNEX

calculations come within 5% of Snay's theoretical results and the Wigwam measurements. If we accept the 20% instrumentation error in the Wigwam measurements, the agreement between the LASNEX calculations and the Wigwam data is extremely good. In the high-pressure region where Snay's treatment, which assumes a point energy source and ignores the device size, is expected to produce inaccurate results, the computation is about 10% lower. The good agreement of the LASNEX calculations with the Wigwam measurements is quite unexpected, because the code calculation is by no means an exact simulation of the real world. We used an equation of state⁷ for pure, homogeneous and isotropic water, whereas ocean water is neither homogeneous nor isotropic. However, we believe that the good agreement was not fortuitous and resulted for the following reasons:

1. The equation of state describing P- ρ -T relations is not very sensitive to the mixing of impurities.
2. Although the radiation opacity is sensitive to impurities, the water is already optically very thick, and the additional opacity due to the impurities does not significantly alter the fireball produced by the x rays.
3. The scale of anisotropy in the ocean caused by a temperature gradient or gravitational overpressure is on the order of kilometers (the overpressure increases by 1 bar every 10 m). The dimensions in our problems were smaller than the scale of anisotropy in the ocean.

The plots in Fig. 2 clearly demonstrate the usefulness of the cube root scaling law, namely, the blast wave from underwater explosions can be scaled by a cube root of the yield. When the range is expressed in a reduced form by dividing by $Y^{1/3}$, the yield of the explosion is effectively removed, and the blast wave is presented as a wave generated by a 1-kt explosion.

The computed pressures in the very weak shock (less than 0.05 GPa) regime in Fig. 2 are slightly lower than given by Snay's empirical fit, Eq. (2). This may be due to the fact that the artificial viscosity tends to spread the shock front and also because the spreading of the wave front results in an inaccurate calculation of the pressure. These numerical effects, i.e.,

artificial viscosity, truncation error, etc., become more pronounced in proportion to the peak pressure as the wave decays into the weaker and weaker regime.

The time-constant data in Table 2 are plotted in Fig. 5. Because the exact determination of wave profiles in computer simulation is quite difficult, estimating the time constant of waves is not an easy task. Also the field measurement of time constants is more difficult than the measurement of other parameters such as shock arrival time, peak pressure, etc. For this reason, the agreement in Fig. 5 between Snay's theoretical results and the LASNEX calculations is only 20%. In particular, Snay's empirical formula [Eq. (4)] for the low-pressure region comes close to either Snay's theoretical results or the LASNEX calculations only within a limited range.

The computation gives a time constant greater than the one given by Snay's empirical fit, Eq. (4). This disagreement in time constants is quite consistent with the fact that the calculated pressure is lower than the empirical pressure [Eq. (2)]. When the shock front is spread by artificial viscosity, the peak pressure is reduced and the time constant increased. The computation also gives a time constant that is greater than the one from the similarity solution, Eq. (5). This disagreement comes about because the wave at high pressures is not exponential as is shown by the semilog plots in Figs. 4 and 7. We measured the slope at straight lines drawn to represent the average decay curves of the semilog plots, and thus obtained a time constant that is greater than the true decay time.

SUMMARY

We have demonstrated the applicability of the LASNEX code to underwater explosion calculations by simulating the Wigwam test. Our computed data were compared with Snay's theoretical results and the Wigwam measurements. In the intermediate- and low-pressure regions where Snay's theory is expected to be accurate, the computed data come within 5% of Snay's results and of the Wigwam measurements. Our computations agree with the cube root scaling law for the underwater blast wave.

Comparison of the time constants shows less agreement. The LASNEX calculations and Snay's theoretical results come only within 20% of each other. Furthermore, Snay's empirical formula appears to be valid in a limited

range at very low pressures, whereas a time-constant formula based on Sedov's similarity solution is good at very high pressures, leaving the intermediate pressure range with no formula.

These 1-D calculations clearly set the stage for more elaborate 2-D calculations to follow. To examine problems of any practical importance, the effects of the water surface must be considered. This can be done only by 2-D calculations. The water surface and the depth of burst have significant effects on wave propagation in water. By testing the code on 1-D problems, a strong argument can be made for the credibility of the costly and more involved 2-D calculations.

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