Detonations Near the Water Surface

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by

Charles L. Mader
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ABSTRACT

The results of an experimental and theoretical study of
the compressible flow resulting from a sphere of 9404 explosive
initiated at its center and partially immersed in water are
described. The flow was studied experimentally using radiog-
ographic and photographic techniques. Compressible hydrodynamic
calculations were performed using multicomponent Eulerian numer-
cical techniques.

1. INTRODUCTION

The prediction of water waves generated by large-
yield explosions has been based on extrapolation of
empirical correlations of small-yield experimental
data. The accuracy of such predictions is unknown
so there is a need for a detailed description of the
mechanism by which waves are generated by explosions.
The effect of detonation depth needs to be better
understood. The "upper critical depth," i.e., the
depth at which a peak of the wave amplitude occurs,
is not understood. The effects near the explosion
when the flow is quite compressible, such as surge,
shock wave propagation, separation of the shock
wave from the bubble, and the wave pattern near the
explosion have previously received little theoreti-
cal or experimental attention in the region of the
upper critical depth.

This is a progress report of a study of the
early interaction of the detonation products with
the water and air interfaces and the resulting wave
profile near the detonation. The initial phase of
this study was described in Ref. 1.

To determine if compressible hydrodynamic cal-
culations were feasible, given the techniques de-
veloped during the last 15 years for describing de-
tonation phenomenon and equations of state, the early
time behavior of the diverging detonation was cal-
culated and compared with experimental radiographic
results. The calculated results were also compared
with detailed early time measurements of the shock
wave in water produced by a diverging detonation
and with late time measurements where the interac-
tion of the detonation products and the water was
followed for at least one complete oscillation of
the bubble. The observed agreement between the
observed short- and long-time behavior of an under-
water detonation and the detailed one-dimensional
compressible hydrodynamic calculations suggests
that the calculated energy partition between de-
tonation products and the water is sufficiently ac-
curate to be used in multidimensional studies of wave-
generation mechanisms.

II. PHERMEX EXPERIMENTAL RESULTS

The Los Alamos Laboratory radiographic facility
PHERMEX\(^2\) (Pulsed High Energy Radiographic Machine
Emitting X-Rays) is a radiographic facility which
produces an x-ray pulse by impinging 27-MeV elec-
trons, generated by a standing wave linear accel-
erator, upon a 0.7-mm diam. tungsten target. Radia-
tion intensities of 5.0 R are obtained at the experi-
tmental system being studied (positioned approxi-
mately 3 m from the target). An x-ray film is
placed approximately 0.75 m behind the experimental
system in a protective aluminum case. This arrange-
ment gives radiographic resolution of ± 0.1 µsec
and ± .02 cm without time smear.
A sphere of explosive consisting of a 0.635-cm radius PETN (Estes XTX8003, 80/20 by wt. PETN/silicone binder) and 0.635 cm of 9404 was detonated at the center. The sphere was placed half in the water in the radiographs taken at 15.8 and 26.3 μsec after detonation was initiated. The detonation wave arrived at the explosive surface in 1.5 μsec. The sphere was placed two-thirds in the water in the radiograph taken at 61.3 μsec. The position of the water-detonation product interface, the splash wave and the water shock wave may be determined from the radiographs. The static and dynamic radiographs and sketches of the prominent features of the radiographs are shown in Figs. 1, 2, and 3.

One-dimensional S1 calculations similar to those described in Ref. 1 were performed for the explosive sphere in water at one atmosphere density and in air at one Los Alamos atmosphere. The water equation-of-state parameters used were identical to those described in Ref. 1. The equation-of-state parameters used for 9404, PETN, and air are given in Table I. The position of the water shock and bubble radius as a function of time are shown in Fig. 4. Also shown are the positions found in the radiographic study shown in Figs. 1, 2, and 3. The calculated pressure of the water shock and the 9404-water interface are shown in Fig. 5. The position of the air shock and the 9404-air interface as a function of time is shown in Fig. 6. The calculated pressure of the air shock and the 9404-air interface as a function of time is shown in Fig. 7. Since the position of the water-detonation product interface and the water shock wave along the vertical axis in the radiographs is in good agreement with the one-dimensional calculations, we used the results of the one-dimensional calculations to obtain estimates of the pressures in the water and the positions of the air shock, air-detonation product interface, and the pressures along the vertical axis at the times of the radiographs. The results of this exercise are sketched in Fig. 8.

### Table I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PETN</th>
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The gas bubble 302 μsec after the load ring pulse. A wax shutter was used to prevent overexposure. The time was chosen so that the surface-wave tip, if resolved, would be within the field. The wave tip was obscured by detonation products but the gas bubble (products/water) interface was clearly resolved. The bubble radius was 8.03 cm. Another camera, the GMX-6 Dynafax framing camera, viewed a 36-in. by 36-in. field, which was below water level. Back lighting for this camera was accomplished with the GMX-2 electronic xenon flash unit and a diffusing screen made from Mylar drafting paper. The camera was operated at 2151 rps so that the nominal time between frames was 29 μsec; exposure time was 1 μsec per frame. The third camera was a Bolex H-16 Reflex cine camera with a framing rate of 64 frames per second and exposures times of 0.002 sec per frame. Quantitative data obtained from the first two cameras are plotted in Fig. 10. Also shown are the results of one-dimensional SIN hydrodynamic calculations for the explosive system immersed in water at 1 bar. The deviation becomes significant after 100 μsec. Two-dimensional hydrodynamic calculations will obviously be required to describe the flow after later times.

The results from the cine camera are shown in Figs. 11 and 12. Since these data are affected by bottom and side effects in the geometry used, additional experiments in a larger tank will be required to determine the magnitude of such effects.
IV. TWO DIMENSIONAL COMPRESSIBLE HYDRODYNAMIC CALCULATIONS

The EIC code, which uses the Particle-In-Cell (PIC) method, was used to study the dynamics of a sphere of 9404 detonated at the water surface. Particle plots are shown in Fig. 13. The calculated position along the vertical axis was in agreement with the SIN one-dimensional calculations described previously. The splash wave was not as large or as high as observed and the detonation products and air shock did not travel as far as predicted by the SIN calculations. Since the resolution available from a PIC calculation is severely limited, such disagreement may be expected. The calculations did indicate that larger splash waves occur with time and increasing water depth.

The 2DE code has recently been developed to calculate multicomponent reactive hydrodynamic problems in slab or cylindrical geometry using continuous Eulerian equations of motion. Numerical solutions of severely distorted flow problems, such as the interaction of shocks with V notches, cylindrical voids, and aluminum rods in water, have given results that closely reproduced those observed experimentally. The high resolution available with the technique makes it attractive for problems with large distortions such as the problem of the explosive sphere interacting with a water surface. The present code gives accurate solutions for mixed cells with two components, but approximations are necessary if three or more components are present in a cell. Since the splash wave results in cells of water, detonation products and air, the region of the splash wave is not as accurately defined as the rest of the flow.

One-dimensional SIN calculations indicated that the results of the calculation were only slightly changed if the PETN-9404 explosive sphere was replaced by an all 9404 explosive sphere with the inner 0.9-cm radius initially detonated at constant volume. The larger "initiator" was necessary in the two dimensional calculations because of the large cell size used for economy reasons.

The 2DE calculations were performed with a mesh of 100 cells in the Z direction and 50 or 100 cells in the R direction. Several cell sizes were tried. The largest cell size that would give results independent of the mesh size was 0.0635 cm, which gave 20 cells along the radius of the explosive sphere. Smaller cell size would be required for definition of the splash wave; however, a more exact treatment of the three component cells would be necessary before such calculations could be justified. A smaller cell size would also permit a better description of the air shock and the 9404-air interface.

Calculations were performed for the 9404 sphere completely immersed under 1.27 cm of water. The isoplot of the calculated flow are shown in Fig. 14. Calculations were performed for the 9404 0.625 immersed in water. The isoplot of the calculated flow are shown in Fig. 15.

A comparison of the 2DE calculated position of the water shock, 9404-water interface, and the water shock pressure as a function of time, and the one-dimensional SIN results are shown in Fig. 16. A similar comparison for the air shock and 9404-air interface is shown in Fig. 17. The 2DE calculation did not resolve the position of the air shock.

Agreement between the various calculations is necessary during the early part of the flow if the calculations are accurate. The agreement is remarkable and suggests that the 2DE calculations may be trusted within the numerical resolution.

V. DISCUSSION

In his studies of the underwater explosion pulsation problem, Pritchett has demonstrated that theoretical results that include the effect of compressibility tend to agree with the incompressible water calculations. Since the calculations described in this report and in Ref. 1 show that the flow is determined by the impulse and resulting momentum imparted to the water by the time the shock wave in the water has traveled three to five radii of the initial explosive, it is clear that, if the initial impulse assumed by the incompressible calculation is approximately correct, the remainder of the flow should be accurately described by the incompressible assumption. These results suggest that we have already solved the compressible flow problem for a sufficient interval to give us a good first approximation of the initial conditions to use in an incompressible calculation. Further numerical studies should probably be performed with either a good incompressible technique that accurately
describes the surface boundary or an almost incom-
pressible technique such as ICE.  

As mentioned in the introduction, we are in-
terested in the region of the upper critical depth.
The upper critical depth has been elegantly re-
viewed by Le Mehaute. In regard to this phenomena,
the calculations show that the water in and near the
splash wave has a large amount of momentum. In par-
ticular, as shown in Fig. 17, the velocity in the
radial direction is up to 5 times larger in the wa-
ter near the splash wave than in the rest of the
shocked water. This concentration of momentum near
the water surface could be a contributing factor to
the phenomenon of upper critical depth. Whether or
not it is important for the late-time wave behavior,
it is the reason that the observed horizontal bubble
radius is larger than the vertical bubble radius for
explosions near the water surface, as shown in Figs.
4 and 10. 

The high velocity present in the splash wave is
a result of the initial water shock being quickly
rarefied and permitting a second shock to be de-
ivered from the explosive products. Subsequent
shocks and rarefactions occur while the detonation
products still have high pressures. Each reverbera-
tion increases the particle velocity of the splash
wave by an increment that decreases as the pressure
of the driving detonation products decreases. The
particle velocity of the remainder of the water can-
not be increased by reverberations during the early
high-pressure motion since a free interface is not
available.

The estimated period of a 1.27-cm radius 9404
sphere immersed in water at 1 bar pressure is 0.1
sec and the maximum bubble radius is 44.2 cms. As
shown in Fig. 12, the observed maximum radius is
slightly larger and the period is 4 to 5 times
larger than the estimated radius and period. The
large momentum of the water near the surface of the
bubble is consistent with this observation.

The late-time experimental data shown in Fig.
11 suggests that the plumes formed after collapse
of the bubble may be the primary source of the
large waves characteristic of the upper critical
depth. B. G. Craig of GMX-8 is presently studying
the long-term plume and wave behavior for the A.E.C.
Tamarin committee. The results of this study may
indicate where future theoretical studies should be

ACKNOWLEDGMENTS

The radiographic study was performed by Roger
The photographic study was performed by G. B. Craig
of GMX-8 and John Taylor of GMX-6. The author
gratefully acknowledges the suggestions and con-
tributions of Kenneth Olsen of J-9, James D. Kershner
of T-4, Gaylord Miller of NOAA Environmental Research
Laboratories, Bernard Le Mehaute of Tetra Tech, Inc.,
John Pritchett of Information Research Associates,
and William G. Van Dorn of Scripps Institution of
Oceanography.

These studies have been performed for the

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Fig. 1.
The static and dynamic radiograph at 15.8 μsec of a 1.27-cm radius explosive sphere detonating half immersed in water. A sketch of the prominent features of the radiograph is shown.

Fig. 2.
The static and dynamic radiograph at 26.3 μsec of a 1.27-cm radius sphere of 9404 detonating half immersed in water. A sketch of the prominent features of the radiographs is shown.
Fig. 3.
The static and dynamic radiograph at 61.3 μsec of a 1.27-cm radius sphere of 9404 detonating two-thirds immersed in water. (The dynamic radiographs also shows some New Mexican folk art added by the technician.) A sketch of the prominent features of the radiograph (sadly without any folk art) is shown.

Fig. 4.
The water shock and explosive-water interface radius as a function of time for a 1.27 cm radius explosive sphere in water at 1 bar. Also shown are the positions determined from the radiographic study.
Fig. 5. The water shock and explosive-water interface pressure as a function of time for a 1.27-cm radius explosive sphere in water at 1 bar.

Fig. 6. The air shock and explosive-air interface radius as a function of time for a 1.27-cm radius explosive sphere in air at one Los Alamos atmosphere.
Fig. 7.
The air shock and explosive air interface pressure as a function of time for a 1.27-cm radius explosive sphere in air at one Los Alamos atmosphere.

Fig. 8.
Sketches of the important features of the flow of a 1.27-cm radius explosive sphere interacting with a water-air interface at the times used in the radiographic study. The calculated one-dimensional pressures in bars and positions of the air shock and air-detonation-product interface in centimeters are shown along the vertical axis.
Fig. 9.
The experimental arrangement for the photographic study.

Fig. 10.
The detonation product-water radius calculated using the one-dimensional model and the experimental data as a function of time. The experimental data is shown with a bar whose top is the horizontal radius and bottom is the vertical radius through the initial center of the explosive charge.
Fig. 11.
Selected frames from the cine camera data. The time between frames was 0.0156 seconds, the exposure time was 0.002 seconds per frame. The grid behind the shot was 4 in. between lines.
Fig. 12.
Preliminary cine camera data of the detonation product-water radius as a function of time.

Fig. 13.
PIC (Particle-In-Cell) calculations of a 1.27-cm radius sphere of 9404 initiated at its center and immersed in water at various levels. The "X" plotting symbols on the left indicate the position of cells that have been shocked to temperatures greater than ambient.
Two-dimensional Eulerian calculations of a 1.27-cm radius 9404 sphere initiated at its center by a 0.4-cm radius initiator and immersed under 1.27-cm of water. The pressure contour interval is 20 kbars, the density contour interval is 0.2 gm/cc, and the velocity contour interval is 0.05 cm/μsec. The position of mixed cells (9404-water, 9404-air, water-air or 9404-water-air) is shown with an "X" plotting symbol.
pressure

Fig. 14. (cont)
density

Fig. 14. (cont)
density

Fig. 14. (cont)
Velocity in \( R \) direction

Fig. 14. (cont)
Velocity in R direction

Fig. 14. (cont)
Velocity in Z direction

Fig. 14. (cont)
Velocity in Z direction

Fig. 14. (cont)
Fig. 15.
Two-dimensional Eulerian calculations of a 1.27-cm radius 9404 sphere initiated at its center by a 0.4-cm radius initiator and immersed to a depth of 1.5875 cm. The contour intervals are the same as Fig. 14.
density

Fig. 15. (cont)
velocity in R direction

Fig. 15. (cont)
velocity in Z direction

Fig. 15. (cont)
Fig. 16.
Calculated position of the water shock, 9404-water interface and water shock pressure as a function of time for the SIN and 2DE calculations.

Fig. 17.
Calculated position of the air shock and the 9404-air interface as a function of time for the SIN and 2DE calculations.