WATER WAVES PRODUCED BY CRATERING EXPLOSIONS IN SHALLOW WATER

W. J. Garcia, Jr.

October 20, 1970

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

Reproduced From
Best Available Copy

20000922 112
WATER WAVES PRODUCED BY CRATERING EXPLOSIONS IN SHALLOW WATER

W. J. Garcia, Jr.
Contents

Abstract .................................................. 1
The Data ................................................... 1
Analysis .................................................... 3
Conclusions ............................................... 5
References ............................................... 6
WATER WAVES PRODUCED BY CRATERING EXPLOSIONS IN SHALLOW WATER

Abstract

In the course of developing the capability of predicting the characteristics of water waves generated by explosions detonated in shallow water beneath the ocean floor, the pertinent data from past experiments were analysed using dimensional analysis as a framework. Data were examined from one series of high explosive cratering experiments detonated beneath the floor in shallow water, and from two series of high explosive experiments and one nuclear explosive experiment detonated above the floor in shallow water. The data indicate that the maximum radius of the water column produced by the explosion is proportional to the cube root of the ratio of explosive yield to ambient pressure at the point of detonation. Further, the data show that the maximum radius of the column of water is proportional to the square root of the product of wave height and distance from the source. The conclusions of this scheme of analysis are being tested with hydrodynamic computer code calculations.

The Data

The data from explosion tests fired under the ocean floor in shallow water were analysed in order to gain information about the relationship between the characteristics of the water waves generated and the parameters of the explosion. Very few data are available since there have been few explosive tests of this type. All the available U.S. data are listed in Table 1.

The U.S. Army Engineer Nuclear Cratering Group conducted a series of underwater cratering tests called Project Tugboat.\(^1\),\(^2\) The tests consisted of four one-ton explosions detonated at different depths of burial in the ocean floor, one 10-ton explosion, two 20-ton explosions and one 40-ton explosion, all detonated beneath the ocean floor. The 20-ton and 40-ton explosions actually consisted of two and four charges of 10 tons each, respectively, separated horizontally by 100 to 120 ft. For the purposes of this analysis the 20-ton and 40-ton shots are assumed to be single charges. The explosive used in these tests was aluminized ammonium nitrate slurry, considered here to be equivalent in energy released to 1.62 TNT. These tests were underwater cratering experiments and were detonated in coral reef material. High speed motion pictures were taken of the test shots, and water wave measurements were made.

The Navy's Project HEAT\(^3\) consisted of ten shots of two tons each fired at
Table 1. Experimental data.

<table>
<thead>
<tr>
<th>Y</th>
<th>D</th>
<th>D&lt;sub&gt;w&lt;/sub&gt;</th>
<th>R&lt;sub&gt;c&lt;/sub&gt;</th>
<th>R</th>
<th>H</th>
<th>HR</th>
<th>Y&lt;sub&gt;(D+33)^{1/3}&lt;/sub&gt;</th>
<th>HR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.62</td>
<td>15.5</td>
<td>4.6</td>
<td>47</td>
<td>163</td>
<td>2.96</td>
<td>483</td>
<td>0.322</td>
<td>483</td>
</tr>
<tr>
<td>1.62</td>
<td>19.1</td>
<td>5.0</td>
<td>50</td>
<td>206</td>
<td>1.54</td>
<td>317</td>
<td>0.314</td>
<td>317</td>
</tr>
<tr>
<td>1.62</td>
<td>23.2</td>
<td>5.1</td>
<td>50</td>
<td>80</td>
<td>4.02</td>
<td>321</td>
<td>0.306</td>
<td>370</td>
</tr>
<tr>
<td>1.62</td>
<td>25.8</td>
<td>5.0</td>
<td>46</td>
<td>161</td>
<td>1.97</td>
<td>317</td>
<td>0.302</td>
<td>306</td>
</tr>
<tr>
<td>16.2</td>
<td>42.5</td>
<td>6.5</td>
<td>98</td>
<td>161</td>
<td>11.4+</td>
<td>1835+</td>
<td>0.599</td>
<td>1600</td>
</tr>
<tr>
<td>32.4</td>
<td>42</td>
<td>~10</td>
<td>—</td>
<td>1430</td>
<td>~1.5</td>
<td>~2140</td>
<td>2260</td>
<td></td>
</tr>
<tr>
<td>32.4</td>
<td>42</td>
<td>~10</td>
<td>—</td>
<td>1490</td>
<td>~1.5</td>
<td>~2240</td>
<td>2370+</td>
<td></td>
</tr>
<tr>
<td>64.8</td>
<td>42</td>
<td>~10</td>
<td>—</td>
<td>1950</td>
<td>~1.5</td>
<td>~2920</td>
<td>3090</td>
<td></td>
</tr>
</tbody>
</table>

Mono Lake. Explosive: TNT.

<table>
<thead>
<tr>
<th>Y</th>
<th>D</th>
<th>D&lt;sub&gt;w&lt;/sub&gt;</th>
<th>R&lt;sub&gt;c&lt;/sub&gt;</th>
<th>R</th>
<th>H</th>
<th>HR</th>
<th>Y&lt;sub&gt;(D+33)^{1/3}&lt;/sub&gt;</th>
<th>HR</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.61</td>
<td>10.0</td>
<td>65</td>
<td>1360</td>
<td>0.56</td>
<td>751</td>
<td>0.475</td>
<td>807</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>621</td>
<td>1.06</td>
<td>659</td>
<td>0.475</td>
<td>1010</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.62</td>
<td>13.8</td>
<td>70</td>
<td>4615</td>
<td>0.19</td>
<td>875</td>
<td>0.463</td>
<td>724</td>
</tr>
</tbody>
</table>

Project "Heat." Explosive: HBX-1 (equivalent 1.48 TNT).

<table>
<thead>
<tr>
<th>Y</th>
<th>D</th>
<th>D&lt;sub&gt;w&lt;/sub&gt;</th>
<th>R&lt;sub&gt;c&lt;/sub&gt;</th>
<th>R</th>
<th>H</th>
<th>HR</th>
<th>Y&lt;sub&gt;(D+33)^{1/3}&lt;/sub&gt;</th>
<th>HR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.93</td>
<td>11.04</td>
<td>11.46</td>
<td>66.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.406</td>
<td></td>
</tr>
<tr>
<td>2.92</td>
<td>11.74</td>
<td>12.00</td>
<td>67.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.402</td>
<td></td>
</tr>
<tr>
<td>2.93</td>
<td>11.42</td>
<td>11.58</td>
<td>67.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.405</td>
<td></td>
</tr>
<tr>
<td>2.93</td>
<td>4.69</td>
<td>9.63</td>
<td>62.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.426</td>
<td></td>
</tr>
<tr>
<td>2.93</td>
<td>4.75</td>
<td>9.25</td>
<td>67.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.426</td>
<td></td>
</tr>
<tr>
<td>2.92</td>
<td>4.96</td>
<td>5.04</td>
<td>67.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.425</td>
<td></td>
</tr>
<tr>
<td>2.93</td>
<td>5.00</td>
<td>5.08</td>
<td>62.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.425</td>
<td></td>
</tr>
<tr>
<td>2.92</td>
<td>4.79</td>
<td>5.12</td>
<td>62.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.425</td>
<td></td>
</tr>
<tr>
<td>2.92</td>
<td>4.80</td>
<td>7.88</td>
<td>64.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.425</td>
<td></td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Y</th>
<th>D</th>
<th>D&lt;sub&gt;w&lt;/sub&gt;</th>
<th>R&lt;sub&gt;c&lt;/sub&gt;</th>
<th>R</th>
<th>H</th>
<th>HR</th>
<th>Y&lt;sub&gt;(D+33)^{1/3}&lt;/sub&gt;</th>
<th>HR</th>
</tr>
</thead>
<tbody>
<tr>
<td>23,000</td>
<td>90</td>
<td>140</td>
<td>~1000</td>
<td>1000</td>
<td>94</td>
<td>94,000</td>
<td>5.72</td>
<td>100,000</td>
</tr>
<tr>
<td>2000</td>
<td>47</td>
<td>94,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td>24</td>
<td>96,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td>16</td>
<td>96,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8000</td>
<td>13</td>
<td>104,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td>11</td>
<td>110,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12000</td>
<td>9</td>
<td>108,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Y = Explosive yield, tons TNT.

D = Depth of submergence, feet of sea water.

D<sub>w</sub> = Depth of water, feet.

R<sub>c</sub> = Maximum radius of water column, feet.

R = Distance, feet.

depths varying from the ocean floor to mid-depth in the water. The explosive used was HBX-1, assumed to be equivalent in energy released to 1.48 TNT. In these
tests, high speed motion pictures were taken to determine mound characteristics, column diameter, etc.; however, no water wave measurements were made.

At Mono Lake two explosive charges of 4.6 tons of TNT each were fired at the bottom in shallow water. Water wave measurements and measurements of the column dimensions were made.

In addition to these few high explosive tests, Glasstone reports the results of the Bikini test Baker, a 23 kt nuclear detonation in shallow water. He reports the measured wave heights, the range at which these measurements were made, and the approximate column radius.

Analysis

An empirical approach was used in the analysis of the data; however, dimensional analysis provided the basic relationships among the variables involved. Two useful dimensionless products emerge:

\[ \Pi_1 = \frac{L^4 \rho g}{Y} \]  
\[ \Pi_2 = \frac{pL^3}{Y} \]

where \( L \) is a characteristic length (to be specified later), \( Y \) is yield (units of energy), \( p \) is pressure, \( \rho \) is density and \( g \) is the acceleration of gravity. Since we know that the wave energy per unit area is proportional to the square of the wave height (\( H^2 \)) and the total energy is distributed over an area proportional to the square of the radius of the area of the disturbance (\( R^2 \)), we see by dimensional considerations that we can specify the characteristic length factor \( L^4 \), and can rewrite \( \Pi_1 \) as

\[ \Pi_1 = \frac{H^2 R^2 \rho g}{Y} \]  

This product (3) appears promising, since for oscillatory waves due to a central disturbance the product \( HR \) should be constant for a given wave. We plot \( HR \) vs the yield \( Y \) in Fig. 1; the value of \( HR \) is the average for each wave measurement. In all cases \( H \) is the amplitude of the largest wave from crest to the following trough (in most cases this was the first wave in the train). The curves drawn show both the relationship given by Eq. (3) \( HR = C \times Y^{0.5} \) and the relationship determined by a least-squares fit of the data, \( HR = 297 \times Y^{0.576} \). There are insufficient data to make any conclusions concerning the merits of either relation. Figure 1 does indicate, however, that there are other factors which have subtle but significant effects, and that all the experiments examined were not completely similar.

Next we try to specify the length factor \( L^3 \) in the dimensionless product \( \Pi_2 \). It is known that depth of burst plays a significant role in underwater explosions, since the maximum size to which the bubble grows is a function of the ambient pressure, hence of the depth of burst. Also, the maximum radius of the water column, \( R_c \), is directly related to the maximum size of the gas bubble when it
reaches the surface and vents to the atmosphere. Thus $R_c$ should be related to the yield $Y$ and the overburden pressure $p$; making this assumption leads us to rewrite $\Pi_2$ as

$$\Pi_2 = \frac{p R_c^3}{Y}. \quad (4)$$

Accordingly, Fig. 2 shows a plot of the maximum column radius vs the cube root of the ratio of yield to overburden pressure. The yield $Y$ is expressed in tons to TNT equivalent and the overburden pressure $p$ is expressed in feet of sea water ($p = C \times (D+33)$, where $D$ is depth of submergence in feet). The available data, as can be seen, follow very closely the relation dictated by the product $\Pi_2^{(4)}$.

At this point it was decided to use the maximum column radius to normalize wave height with respect to yield. A plot of the ratio of wave height to maximum column radius ($H/R_c$) vs the ratio of

---

**Fig. 1.** Product of wave height $\times$ distance (average for each measurement) vs yield.

**Fig. 2.** Maximum radius of water column, $R_c$, plotted against a function of the yield $Y$ (tons TNT equivalent) and the depth of burst $D$ (feet).
\[ \frac{H}{R_c} \times 10^2 = 0.157 \]

**Fig. 3.** Ratio of wave height to column radius \( (\frac{H}{R_c}) \) plotted against ratio of distance to column radius \( (\frac{R}{R_c}) \), for all available underwater explosion data.

\[ R_c = 156 \left( \frac{Y}{D+33} \right)^{1/3} \]

where \( Y \) is yield and \( D \) is depth of burst.

The value of \( \frac{H}{R_c} \) shown is the average for each wave measurement. The average percent difference of these data from the best fit curve \( \left( \frac{H}{R_c} \right)^{1/2} = 60.7 \left[ \frac{Y}{(D+33)} \right]^{1/3} \) is 6%. The effects of changes in water depth on the wave height were not considered due to lack of data.

**Fig. 4.** Product of wave height \( \times \) distance (average for each measurement) vs function of yield \( Y \) and depth of burst \( D \).

---

**Conclusions**

In this paper the author has assembled all the relevant U.S. underwater test data for the water wave problem, and has found a framework for interpretation based on similitude. The prediction of water wave phenomena resulting from nuclear explosions beneath the ocean floor may indeed be possible using this physical framework. However, hydrodynamic code calculations at intermediate to high yields are required to confirm this scheme in the absence of full-scale experimental data. Currently, calculations are being made which will permit...
the modeling of underwater cratering explosions using the ABMAC hydrodynamic code as developed by Viecelli. The flexibility of this code is proving to be very valuable in the simulation of the water wave phenomenon.

References

Distribution

LRL Internal Distribution

Michael M. May/D. Sewell
R. Batzel
A. Biehl
J. Carother
T. Cherry
P. Coyle
L. Crooks/E. Harp
D. Dorn
G. Dorough
F. Eby
E. Fleming
W. J. Garcia
E. Goldberg
J. Hadley
A. C. Haussmann
W. Harford
G. Higgins
F. Holzer
J. Kane
J. Knox
J. Kury
A. Lewis
C. McDonald
P. Moulthrop
W. Nervik
M. Nordyke
T. Perlman
D. Rabb
H. Reynolds
H. Rodean
J. Rosengren
B. Rubin
J. Shearer
B. Shore
E. Teller
J. Toman
W. Vandenberg
J. A. Viecelli
G. Werth
TID Berkeley
TID File

External Distribution

J. S. Kelly
Division of Peaceful Nuclear Explosives
Washington, D.C.

R. E. Miller
D. Thornbrough
Nevada Operations Office
Las Vegas, Nevada

A. R. Wilson
Australian Atomic Energy Commission
NSW, Australia

P. Crooks
Atomic Energy Attache
Australian Embassy
Washington, D.C.

R. L. Wiegel
J. W. Johnson
P. Wilde
University of California
Berkeley, California

W. G. VanDorn
Scripps Institution of Oceanography
La Jolla, California

B. LeMehaute
Tetra Tech, Inc.
Pasadena, California

R. Y. Hudson
U.S.A.E. Waterways Experiment Station
Vicksburg, Mississippi

A. Kamel
Louisiana State University
Baton Rouge, Louisiana

E. Peixotto
U.S.A.E. Waterways Experiment Station
Vicksburg, Mississippi

T. Saville, Jr.
Coastal Engineering Research Center
Washington, D.C.

W. Hoyer
ESSO Product Research
Houston, Texas

TID-4500 Distribution, U-35,
Nuclear Explosions—Peaceful Applications 243

KD/1c/1p

-7-