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THE RESPONSE OF SIMPLE HEAVY STEEL TARGETS TO UNDERBOTTOM EXPLOSION ATTACK

by

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STRUCTURAL MECHANICS LABORATORY

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NOTATION

A	Parameter for shock–wave impulse
b	Half beam of block
c_s	Velocity of sound in steel
c_w	Velocity of sound in water
d	Distance from charge to center of displaced water
d_i	Distance from image charge to center of displaced water
D	Distance from charge to bottom of block
g	Acceleration of gravity
h	Height of block
H	Depth of charge below water surface
I	Impulse of shock wave per unit area
k	Stiffness of spring
l	Half length of block
m_e	Mass of entrained water
m_s	Mass of block
m_w	Mass of displaced water
N	See Equation [2]
P_d	Pressure of diffraction wave
P_i	Pressure in incident shock wave
P_r	Pressure in reflected shock wave
R_m	Maximum first bubble radius
S	Area of bottom of block
T	$2h/c_s$
T_1	Vibration period of block mount in air
T_2	Vibration period of block mount in water
T_{m_1}	Half first bubble period
$\bar{u}$	Average maximum particle velocity of displaced water
v_s	Vertical velocity of block
$v_{s_{oi}}$	Initial peak velocity of block
$v_{s_{of}}$	Final positive maximum velocity
v_w	Vertical mean velocity of displaced water volume in absence of block

W	Charge weight
x	Vertical displacement of water
y	Vertical displacement of block
ρ_s	Density of steel
ρ_w	Density of water

ABSTRACT

Underwater explosion tests were conducted against simple heavy steel targets either at or below the water surface. These tests extend the investigation of simple floating targets to targets considerably heavier than the water they displace. The response of the targets yields an insight into the forces developed on ships by the accelerated water flow accompanying gas-bubble pulsation.

The velocity of the targets was recorded as a function of time. The initial peak velocity and the final maximum velocity were correlated with explosion parameters such as the impulse from the initial part of the shock wave and the maximum positive impulse during the bubble expansion. If appropriate allowances are made for the effects of acoustical impedance, mass, and entrained mass of the targets, the observed velocities agree with those predicted by theory. The final maximum velocity indicates the momentum of the target and its entrained mass equals the momentum of the displaced water and its entrained mass.

INTRODUCTION

Underwater explosion tests have been conducted in the past below simple floating targets of cubical shape and against simple submerged targets of the same shape which had the same weight as the displaced water.[1] The response of these targets, all of which had nearly the same acoustical impedance as water, could be correlated with known underwater explosion phenomena. In general, the targets responded in the same way as would the water which the targets displaced. An additional series of tests was undertaken to show how simple targets possessing various properties responded to explosion attack.[2,3,4] The tests described in this report conclude the investigation on simple models. They concern the response to underbottom explosions of simple heavy targets such as steel blocks, which have a much larger density and acoustical impedance than water and could not be expected to respond in the same way as would the displaced water if the block were absent. The methods of determining velocities are discussed, and the measured values are compared with those predicted by theory.

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[1] References are listed on page 12

THEORETICAL DISCUSSION

We consider first a small steel target which is partially immersed in water. The initial or shock wave phase of the motion and the subsequent motion as the gas bubble expands are considered separately. In the first phase reflection and diffraction phenomena and the elasticity of the target must be considered. In the second phase the inertia of the target and the mass of water displaced by the target govern the response.

A shock wave incident normally upon the bottom of such a target is partly reflected and partly transmitted at the interface. Because of the relatively high acoustical impedance of steel, the reflected wave is initially almost equal in amplitude to the direct wave; i.e., the total peak pressure at the block is almost twice as great as the incident pressure. The transmitted pressure wave enters the steel block and travels to the top, where it is reflected and returns toward the bottom as a tension wave. This tension wave will again be almost completely reflected at the bottom, thus being trapped in the steel block. A part, however, may travel back into the water and, if the tension cannot be taken by the water, may cause cavitation. Furthermore, the shock wave in the water at the side of the target will travel to the free surface of the water at a lower speed than the wave travels in steel, and its reflected wave may also cavitate the water.

As the dimensions of the target are finite, diffraction may occur across the target bottom and alter the pressure at the bottom. This effect might be small for a target with large horizontal dimensions but may be considerable for a target with small dimensions. The forces acting on the target during the first phase arise, therefore, from the incident wave P_i, the reflected wave P_r, and a relief pressure P_d due to diffraction. The pressures in the reflected and incident wave depend on the acoustical impedances of steel and water on the assumption that linear theory holds. Thus, at normal incidence,

$$P_i(t) + P_r(t) = NP_i(t) \qquad [1]$$

where

$$N = \frac{2\rho_s c_s}{\rho_s c_s + \rho_w c_w} = 1.92 \qquad [2]$$

and

$$m_s \ddot{y} = SNP_i(t) + SP_d(t) \qquad [3]$$

Here P_d is the mean instantaneous diffracted pressure averaged over S. This formula, however, is valid only up to the time the shock wave in the block travels from bottom to top and return.

$P_d(t)$ might be sufficiently small so that it can be neglected if the lateral dimensions of the target are large and if the duration of the first shock wave phase is small enough. With these assumptions, the equation can be integrated up to the time $T = 2h/c_s$. Assuming zero velocity of the steel block at $T = 0$, integration yields

$$m_s v_{s_{oi}} = 1.92\, S \int_0^T P_i\, dt \qquad [4]$$

P_i depends on the distance D from the charge to the bottom of the target.

We assume, as in Reference 3, that the impulse I per unit area due to the shock wave in open water, up to a time T, may be expressed in terms of distance D and charge weight W by the formula

$$I = \int_0^T P_i\, dt = A\left(\frac{T}{T_{m_1}}\right) W^{2/3} \frac{1}{D} \qquad [5]$$

The parameter A depends, as indicated, on T/T_{m_1}. For a given time T, A assumes larger values for smaller charges indicating that a greater percentage of the (smaller) available impulse has been trapped in the target. The total impulse delivered to the target up to time T is the integral of I over the bottom area multiplied by N. For a distance large enough that the shock wave may be considered to fall upon the bottom surface at normal incidence,

$$m_s v_{s_{oi}} = 1.92\, A\left(\frac{T}{T_{m_1}}\right) W^{2/3} \frac{S}{D} \qquad [6]$$

or

$$v_{s_{oi}} = \frac{1.92}{m_s}\, A\left(\frac{T}{T_{m_1}}\right) W^{2/3} \frac{S}{D} \qquad [7]$$

This velocity, at time T, will be an initial peak velocity of the block if cavitation occurs at this time. This initial velocity occurs at a very early stage of the explosion attack and acts like a shock on the target.

During the time of cavitation the block will be decelerated, since the pressure in the cavitated region below the bottom is nearly zero and atmospheric pressure acts on the target top. This process causes the cavitation to close up.

At some later time, all phenomena can be explained on the assumption that the water and the block are incompressive. Inertia forces only need to be included in calculations. The water as it acts on the block is subject to acceleration or deceleration as the gas globe pulsates. The equation of the forces should include the effects of the acceleration of the water:[5]

$$m_s \ddot{y} = m_w \ddot{x} - m_e (\ddot{y} - \ddot{x}) \qquad [8]$$

where the double dots indicate the second derivative with respect to time. The effects of pressure are included in the acceleration terms. This equation may be rewritten

$$(m_s + m_e)\ddot{y} = (m_w + m_e)\ddot{x}$$

which yields upon integration

$$(m_s + m_e)v_s = (m_w + m_e)v_w \qquad [9]$$

The initial velocity is taken as zero. The last equation states that the momentum of the target plus its entrained mass of water is equal to the momentum of the displaced water and the entrained mass of water. The velocities may be quite different.

The velocity of the water is known,[6] and its maximum velocity u can be expressed in terms of bubble radius and charge depth. This maximum velocity occurs at about 0.1 of the first bubble period. The average maximum vertical particle velocity $\bar{u}$ of the displaced water can be shown to be[1]

$$\bar{u} = v_w = 18.55\, R_m^2 \left(1 + \frac{H}{34}\right)^{1/2} \frac{1}{lb}\left(\tan^{-1}\frac{lb}{d\sqrt{d^2 + l^2 + b^2}} + \tan^{-1}\frac{lb}{d_i\sqrt{d_i^2 + l^2 + b^2}}\right) \qquad [10]$$

and the final positive maximum velocity $v_{s_{of}}$ of the steel block should therefore be

$$v_{s_{of}} = \frac{m_w + m_e}{m_s + m_e}\; 18.55\, R_m^2 \left(1 + \frac{H}{34}\right)^{1/2} \frac{1}{lb}\left(\tan^{-1}\frac{lb}{d\sqrt{d^2 + l^2 + b^2}} + \tan^{-1}\frac{lb}{d_i\sqrt{d_i^2 + l^2 + b^2}}\right) \qquad [11]$$

Equation [9] includes the effect of the free water surface by including the effect of a charge imaged in the surface.

The entrained mass of water m_e of the target has to be determined for the calculation of the final maximum velocity $v_{s_{of}}$.

Equations [7] and [11] represent two theoretical expressions for peak velocities of the target. The first applies after the initial shock wave phase; the second, at the time of about one-tenth the bubble period. Both of these velocities were measured for comparison with the theoretical values. Equation [11] furthermore, if correct, would support the equation for the flexural response of an extended target to an underwater explosion attack.[7]

TEST METHOD

TEST PROCEDURE

Two different targets were used for measuring the motion of heavy targets.

1. A steel block 10 in. by 11 in. by 5 in. high. The bottom area was the same as that of the small wooden blocks described in Reference 1. The weight of the block, including the velocity meter mounted on it, was 162 lb.

2. A cylindrical steel piston 2 in. in diameter and 5 in. high, with the same bottom area as the wooden bars used in Reference 3. The weight, including velocity meter, was 5.72 lb.

Since the targets were appreciably heavier than the weight of the water they displaced, they were suspended by springs so that their vibration periods were in the order of 0.5 to 1 sec, which was long compared with the duration of the explosion phenomena.

Charges were fired below the center of the target bottom at distances from 3 in. to 100 in. The charges were Hercules Engineer's Special caps either alone or with 7, 15, 25, or 50 grams of Pentolite. The targets were either partially immersed or at 18 in. or 37 in. below the surface.

The velocity acquired by the target was measured with a bar-magnet velocity meter and recorded with a Consolidated oscillograph which had a 2.3-ma/in. galvanometer with a natural frequency of about 800 cps, damped 0.6 to 0.8 of critical damping. The magnet was fixed to the top of the block as described in Reference 1.

METHOD OF DERIVING VELOCITIES

Three typical velocity traces are shown in Figure 1. The curve in Figure 1a shows an initial peak deflection which decreases steadily for a small interval equal to the duration of

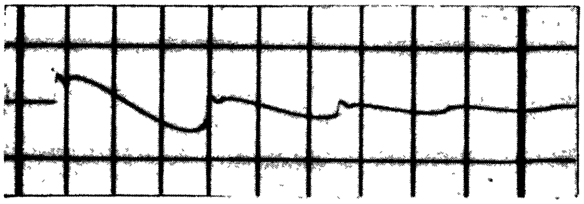

Figure 1a
Charge: Engineer's Special, 15 in. below target
Block has 4.5-in. draft.

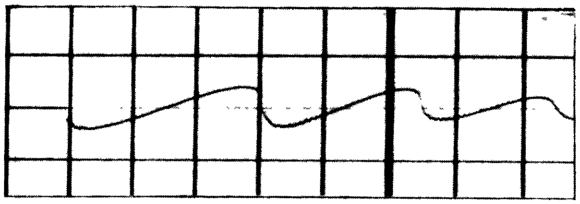

Figure 1b
Charge: Engineer's Special, 15 in. below target.
Top of block is 32 in. below surface.
The velocity meter was connected with reversed polarity.

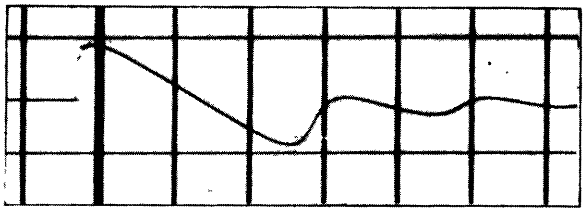

Figure 1c
Charge: Engineer's Special 5 in. below target.
Block has 4.5-in. draft.

Figure 1 – Velocity Meter Records from Surfaced and Submerged Steel Blocks

The vertical lines are 10 msec apart.

cavitation, then increases after the cavitation closes, and thereafter follows a pattern similar to that of the particle motion around a pulsating bubble. The records in Figures 1b and 1c show a hesitation of the deflection but no noticeable decrease due to cavitation. High-speed motion pictures taken during shots fired at close range or with the target submerged failed to reveal cavitation below the block. For instance, no negative slope could be measured for the 25-gram charges closer than 20 in., and pictures taken with the charge at 15 in. did not indicate any cavitation.

The initial peak velocity was derived from the slope of the trace during the period of cavitation. It was corrected for the damping and frequency response characteristics of the galvanometer as discussed in Reference 3.

The final maximum velocity $v_{s_{of}}$ was read from the oscillogram traces at a time of 0.1 of the bubble period.

The accuracy of the measurements for the initial peak velocity $v_{s_{oi}}$ depends largely on the duration of the cavitation phase. The longer the cavitation, the more accurately the slope can be determined. The longest duration for constant slope for a particular charge is obtained at a distance of about the diameter of the gas bubble. The cavitation period increases, furthermore, with charge size, so that the accuracy for larger charges is better than it is for smaller charges. The accuracy of the readings is estimated to range from ±6 to ±10 percent depending on charge size and charge distance to target. For the very small Engineer's Special detonator cap, which is about equivalent to 1.25 grams of Pentolite, the accuracy may even range from ±10 to ±12 percent.

The error in the measurements of $v_{s_{of}}$ is estimated to be in the order of ±6 percent because of inaccuracies in reading the oscillogram traces, in calibrating the velocity meter, and in measuring the maximum bubble radius.

METHOD OF DERIVING ENTRAINED MASS OF WATER

The entrained masses of the targets were determined experimentally by measuring the change of frequency for the spring-mounted targets in air and at various drafts.

The vibration period in air is

$$T_1 = 2\pi \sqrt{\frac{m_s}{k}} \qquad [12]$$

and the period at any draft is

$$T_2 = 2\pi \sqrt{\frac{m_s + m_e}{k + \rho_w Sg}} \qquad [13]$$

Thus

$$m_e = m_s \left[\frac{T_2^2}{T_1^2} \left(1 + \frac{\rho_w Sg}{k}\right) - 1 \right] \qquad [14]$$

The term $\rho_w Sq$, in pounds per inch, could be called the stiffness due to buoyancy.[8]

Tests to determine m_e were conducted by suspending wooden targets of the same dimensions as the steel targets on a coil spring so as to make the entrained mass a reasonable fraction of the mass of the target. The spring stiffness was selected so that the vibrations in air and under water were well in the linear range. The weight of the entrained mass of the steel block changed only slightly for a draft from 2 to 5 in. and was 11 lb, within an error of about 10 percent; the corresponding value for the steel piston was 0.11 lb. The term for the stiffeners due to buoyancy was considered negligible for the completely submerged target, and the weight of the entrained mass for the steel block was found to be 24 lb.

TEST RESULTS AND DISCUSSION

The test results are separated into two groups. For the first group, the draft of the target was held constant at 3 in. and the distance to the charge was varied. For the second group the draft also was varied.

For the first group the observed values of the initial peak velocity $v_{s_{oi}}$ of the steel targets, derived from the oscillograph records, and the corresponding values of $A(T/T_{m_1})$, calculated from Equation [7], are summarized in Table 1. Also listed are the measured values of the final maximum velocity $v_{s_{of}}$. The last column lists the values of $v_{s_{of}}$ calculated from Equation [11].

The values for the initial impulse parameter $A(T/T_{m_1})$ derived from Equation [7] are almost constant for a particular charge. The observed values of A, however, decrease with increasing charge weight, as expected, because T_{m_1} increases and T/T_{m_1} decreases. In Figure 2 the average value of $A(T/T_{m_1})$ for each charge is plotted against the proportionate time T/T_{m_1}. The impulses listed in this report correspond to smaller values of T/T_{m_1} than those reported in Reference 2; they seem to follow a plausible trend.

Note that at the same ranges initial velocities are smaller for the steel piston than for the steel block. Also no values for $A(T/T_{m_1})$ were derived from the initial velocities obtained from shots fired against the steel piston. The assumptions made for Equation [7] cannot be applied. The small horizontal dimensions of the piston allow diffracted pressures to have a large effect on the piston during the transit time of the shock wave. The increase in pressure due to the reflected wave is, therefore, almost completely canceled. For this reason the initial velocities are 40 to 50 percent lower than those for the steel block.

Final maximum velocities $v_{s_{of}}$ are plotted in Figure 3 against distance from charge to target. The points are measured values; the curves are calculated according to Equation [11]. It can be seen that Equation [11] is well verified by experiment.

TABLE 1

Measured and Calculated Velocities of Partly Submerged Steel Targets

Distance from Charge to Target in.	Initial Measured Peak Velocity $v_{s_{oi}}$ fps	Initial Impulse Parameter $A(T/T_{m_1})$	Measured Final Maximum Velocity $v_{s_{of}}$ fps	Calculated Final Maximum Velocity $v_{s_{of}}$ fps
Steel Block, Draft 3 in.				
Engineer's Special Detonator Cap; $T_{m_1} = 15.5$ msec; $R_m{}^* = 7.25$ in.				
80	0.234	1.92	0.062	0.047
60	0.318	1.93	0.086	0.084
40	0.467	1.93	0.157	0.16
20	0.93	1.89	0.515	0.60
7 grams of Pentolite plus Detonator; $T_{m_1} = 27.5$ msec; $R_m = 13.6$ in.				
80	0.635	1.49	0.16	0.16
60	0.83	1.43	0.255	0.29
40	1.3	1.51	0.51	0.58
20	2.1	1.22	1.9	2.1
15 grams of Pentolite plus Detonator; $T_{m_1} = 33.5$ msec; $R_m = 17$ in.				
80	0.93	1.38	0.23	0.25
60	1.2	1.28	0.46	0.46
40	1.8	1.35	1.05	0.93
20	3.05	1.13	3.15	3.3
25 grams of Pentolite plus Detonator; $T_{m_1} = 39.5$ msec; $R_m = 20$ in.				
100	0.96	1.29	0.245	0.23
80	1.13	1.22	0.30	0.35
60	1.52	1.20	0.62	0.64
40	2.27	1.23	1.3	1.28
20	4.40	1.18	4.4	4.55
50 grams of Pentolite plus Detonator; $T_{m_1} = 52$ msec; $R_m = 25$ in.				
60	2.02	1.04	0.98	0.99
40	2.96	1.05	2.0	1.97
Steel Piston, Draft 3 in.				
Engineer's Special Detonator Cap; $T_{m_1} = 15.5$ msec; $R_m = 7.25$ in.				
40	0.29	-	-	-
20	0.49	-	0.39	0.39
15	0.75	-	0.67	0.68
10	-	-	1.3	1.3
5	-	-	4.0	4.3

* R_m is the maximum bubble radius during its first expansion.

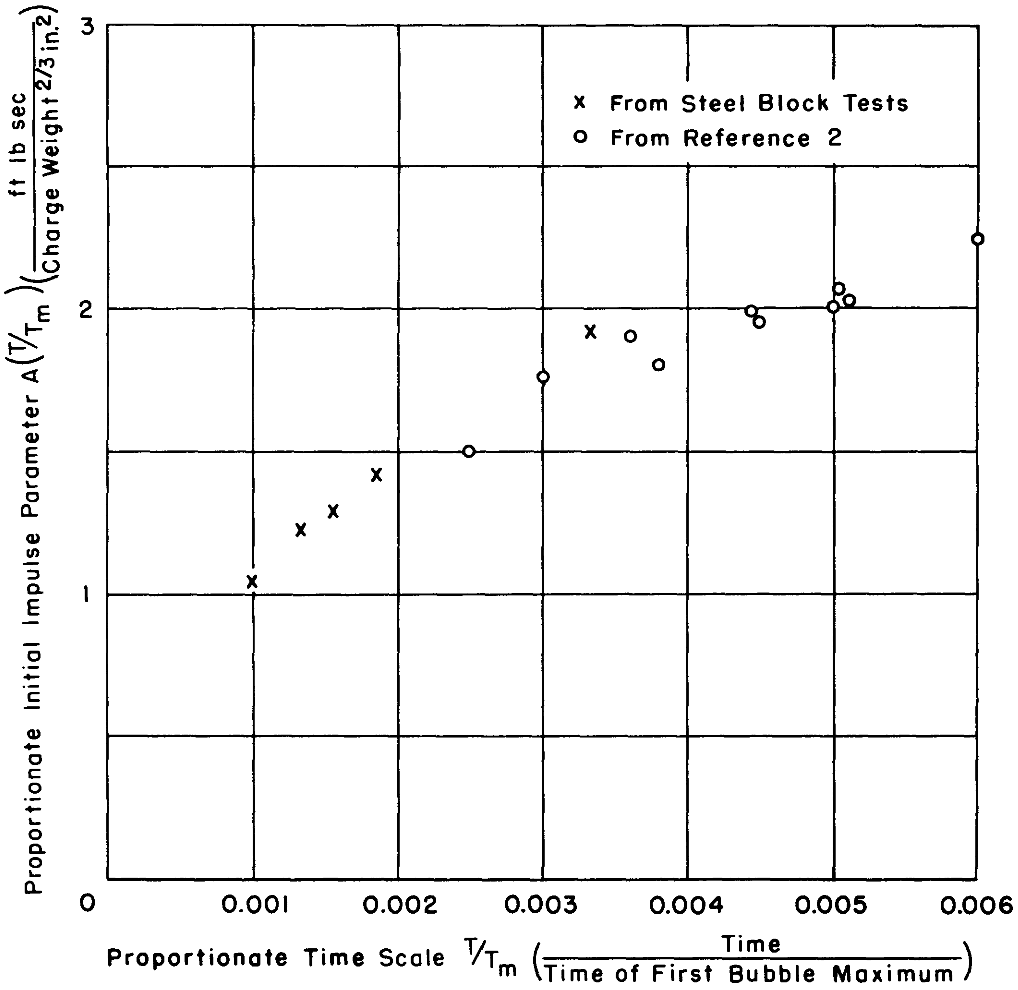

Figure 2 – Proportionate Initial Impulse Parameter versus Proportionate Time

During the second group of tests the draft of the steel block was varied from 2 in. to 5 in. Additional tests were conducted against the completely submerged steel block at depths of 18 and 37 in.

The initial peak velocities, derived from the slope when present, corresponded to those for a draft of 3 in.

The final maximum velocities $v_{s_{of}}$ of surfaced targets at various drafts and of completely submerged targets agreed well with those calculated from Equation [11]; see Table 2. They verify the assumption made in Equation [11] that the final motion of the heavy target is governed by the motion of the water around the pulsating gas bubble.

Equation [11] theoretically is valid only for distances from charge to target bottom large enough so that the acceleration field around the target can be considered uniform. It is of interest to note from Table 2 that the agreement between calculated and measured values of the final maximum velocities is still very good for distances smaller than the first maximum bubble radius. The maximum bubble radius of the detonator is 7 in.; that

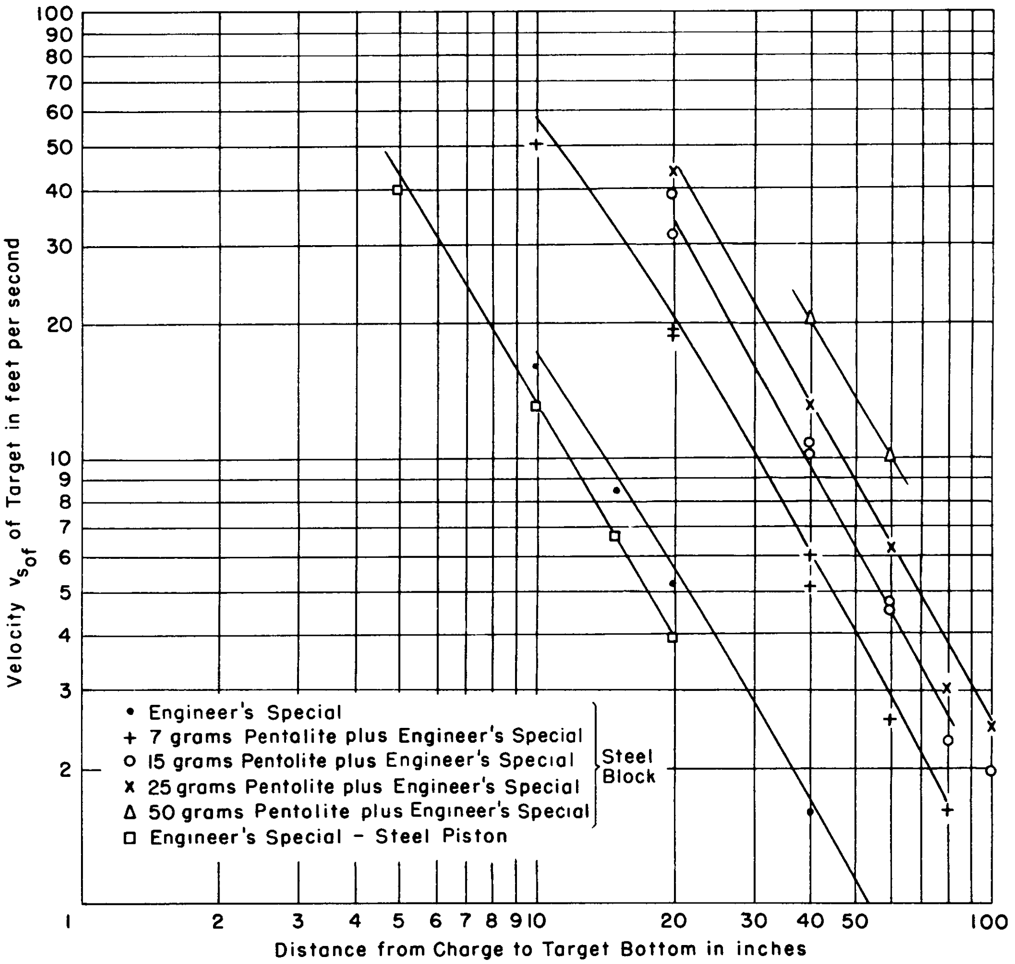

Figure 3 – Final Maximum Velocity $v_{s_{of}}$ versus Distance from Charge to Target Bottom

The points are measured values. The lines are calculated from Equation [11]. The target had a draft of 3 in.

of the 25-gram charge, 20 in.

The method of deriving the forces acting on a body from the average acceleration of the water particles of the displaced water, when the target is not present, gives fairly good results. This method was also used with satisfactory results for calculating the forces acting on ships during underbottom explosion attack.

CONCLUSIONS

1. The initial momentum of a simple heavy steel target at the water surface agrees well with theory. The momentum equals that in the shock wave and the wave reflected from the target in the time prior to cavitation.
2. Diffraction of the shock wave at a steel target with dimensions small compared with

TABLE 2

Measured and Calculated Final Maximum Velocities $v_{s_{of}}$ for Steel Blocks at Varying Draft

Distance from Charge to Target in.	Distance of Target Bottom below Water Surface in.	Final Maximum Velocity fps	
		Measured	Calculated
15	2	0.66	0.75
15	3	0.84	0.81
15	3.5	0.867	0.84
15	4.5	0.90	0.89
15	5	0.96	0.91
40*	18	1.48	1.37
20*	18	3.96	3.90
15*	18	5.94	6.15
10*	18	9.4	10.3
20	37	0.51	0.41
15	37	0.77	0.77
10	37	1.38	1.30
5	37	2.56	2.81

*The charges in these shots were 25 grams of Pentolite plus an Engineer's Special detonator cap; in all other shots only a detonator cap was fired.

the shock wave length may lower the initial momentum considerably.

3. Cavitation was not observed with submerged heavy targets, and the rise to the final maximum velocity was relatively smooth.

4. The final maximum momentum of the target occurs at the time of the maximum velocity of the water particles around the expanding gas bubble.

5. The final maximum momentum equals that of the displaced water in the absence of the target if the entrained mass is added to that of the target and also to that of the displaced water.

6. Forces acting on a body in a pressure field caused by an underwater explosion can be derived from the acceleration of the water particles. This result supports a method previously reported for determining forces acting on a ship during underbottom attack.

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Underwater explosion tests were conducted against simple heavy steel targets either at or below the water surface. These tests extend the investigation of simple floating targets to targets considerably heavier than the water they displace. The response of the targets yields an insight into the forces developed on ships by the accelerated water flow accompanying gas-bubble pulsation.

The velocity of the targets was recorded as a function of time. The initial peak velocity and the final maximum velocity were

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3. Ship hulls – Structural analysis – Model tests
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