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NAVY DEPARTMENT

THE DAVID W. TAYLOR MODEL BASIN

WASHINGTON 7, D.C.

THE IMPULSE GENERATED BY AN UNDERWATER EXPLOSION AS A FUNCTION OF TIME AND DEPTH

by

Erich Buchmann, Ph.D.

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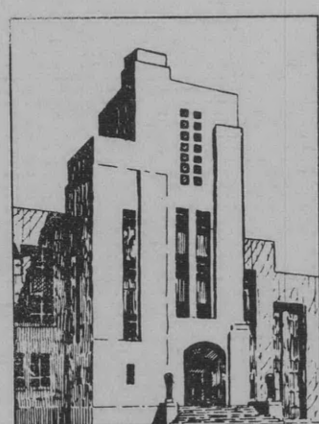

RESEARCH AND DEVELOPMENT REPORT

November 1955 Report 969

NAVY DEPARTMENT
DAVID TAYLOR MODEL BASIN
WASHINGTON 7, D. C.

IN REPLY REFER TO
S81/3
A9/1
(710:MCC:pr)

16 January 1956

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Previous underwater explosion tests against simple floating wooden ·gets indicated that the initial velocity acquired by the target is .ated to the total impulse of the incident pressure wave on the bottom the target up to the time when cavitation occurs and the pressure is luced to zero. To explore this relation more thoroughly, new tests were ıducted in such a way that the time of action of the shock-wave pressure ; varied by changing the height of the target. These new tests are ;cribed in enclosure (1).

As reported in enclosure (1) it was found that the initial momentum ıuired by the target steadily increased with time of action, i. e., .ght of target, over the range tested.

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NS 724-018

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ABSTRACT

Previous underwater explosion tests against simple floating wooden targets have indicated that the initial velocity acquired by the target depends on the duration of the interaction of the shock-wave pressure in the water with the target. This interaction may be interrupted by cavitation below the target; after the cavitation closes up, the momentum of the target becomes the same as that of the water which would occupy its volume if the target were removed.

New tests were conducted in such a way that the time of the action of the shock-wave pressure was varied by changing the height of the target. It was found that the initial momentum acquired by the target steadily increased with time of action over the range tested. The momentum may be considerably larger than that which is due to the initial shock-wave impulse integrated up to 6 to 10 times the time constant.

INTRODUCTION

The response of simple floating wooden targets to underbottom explosions has been discussed in recent reports.[1,2] It was shown that the initial peak velocity acquired by the target is related to the total impulse of the incident pressure wave on the bottom of the target up to the time when cavitation occurs and the pressure is reduced to zero.

This present report describes some tests which were designed to explore this relation more thoroughly. It was believed that by proper choice of test conditions, the time of occurrence of cavitation could be varied in different tests, and the total initial impulse acting on the target could likewise be varied. Hence a measurement of the initial peak velocity of the target in each test would give experimental data on the variation with time of the impulse from a charge. This impulse is an important characteristic of the charge because it is sometimes directly related to the damaging power.

TEST METHOD

The tests were conducted by detonating a small charge below a partially immersed target and measuring the velocity at the top of the target with a bar-magnet velocity meter. The target was a wooden bar, 2 in. in diameter and initially 30 in. long. A 3-in. length of the bar was cut off between successive charges.

The target was suspended vertically from a soft spring, and the charge and a suitable small weight were hung from the bottom so that the draft of the bar was always half its length. The weight was below the charge and was detached from the bar by the explosion. The

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[1]References are listed on page 10.

velocity-meter coil was wound around a light polystyrene tube, 2 in. in diameter and 10 in. long, mounted on top of the wooden bar. The velocity-meter signals were recorded with a Consolidated oscillograph using a galvanometer with a frequency response flat to about 400 cps and a paper speed of about 3 fps.

Army Engineer's special blasting caps (U.S. Army Specification 49-20A) alone and with 3, 7, 15, or 25 gm of pentolite, were fired below the bottom of the bar at distances such that $W^{1/3}/D$ was approximately 0.06, where W is the charge weight in lb and D is the distance from the charge to the bottom of the target in ft. The detonator was considered to be equivalent to 1.25 gm of pentolite. Nine series of shots were fired in all. See Table 1 for test details.

TABLE 1

Test Details

Charge Composition	Equivalent Charge Weight W in lb Pentolite lb	Half Pulsation Period T_{m_1} msec	Distance D from Charge to Bottom of Target** ft
ES*	0.00276	15.5	2.5
ES + 3	0.00940	22.5	3.33
ES + 7	0.01820	27.5	3.33
ES + 15	0.0359	33.5	5.0
ES + 25	0.0580	39.5	6.25

*ES = Army Engineers Special blasting cap, electric, U.S. Army Specifications 49-20A.

**The initial target length of 30 in. was reduced 3 in. between each of nine charges.

In a preliminary test, the sound velocity in the wooden bar was measured by fastening the end of the bar to an electromagnetic shaker and vibrating the bar longitudinally at a variable frequency until resonance was obtained. The sound velocity, equal to twice the length of the bar divided by the vibration period, was 10^4 fps. Also, since the mean density of the bar was 0.0178 lb/in.^{3}, the acoustic impedance of the wood was 5.5 lb-sec/in.^{3} or about the same as for fresh water, 5.4 lb-sec/in.^{3}.

Since the velocity of sound in the wood was approximately twice that in water, the reflected shock waves from the surface of the water and the upper end of the wooden bar should have arrived at the bottom of the bar at the same time, for the draft of the bar was always one-half its length. Also, since the acoustic impedance of water and target were the same, it can be assumed that the pressure wave from the water traveled into the target without modification. After reflection at the upper surface of the bar and return to the bottom surface, the wave would travel back into the water as a tension wave and presumably cause immediate cavitation at the interface. The time required for the shock wave to travel up the bar and return appears to have been increased by the presence of the relatively long velocity meter at the top, judging by the frequency of oscillations observed in the velocity meter traces. However, cavitation in the water around the bar should occur at the time required for the shock wave to travel through the water to the free surface and back to the plane containing the bottom surface of the bar. Because of the test conditions, this time was the same as the *nominal* transit time through the bar. The shock-wave pressure therefore acted on the target only for the time required by the wave to travel up and down through the bar plus a small additional time for diffraction to act across the bottom face of the bar.

The length of time during which the initial positive pressure acted on the target varied from 0.50 msec when the bar was 30 in. long to 0.10 msec for a 6-in. length.

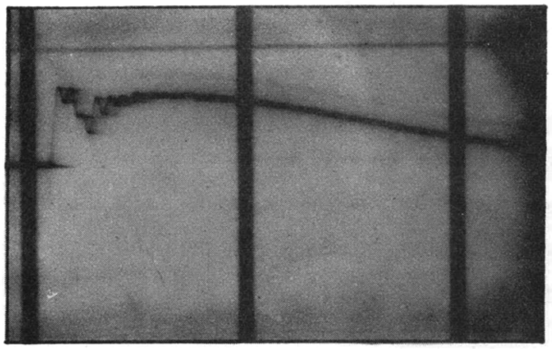
COMPUTATION OF THE MEAN VERTICAL VELOCITY

The response of the bar desired from these tests is the mean vertical velocity of the bar at the time T when cavitation occurs at the bottom of the bar. This velocity may be determined from the oscillograms (samples of which are shown in Figure 1) in the following manner.

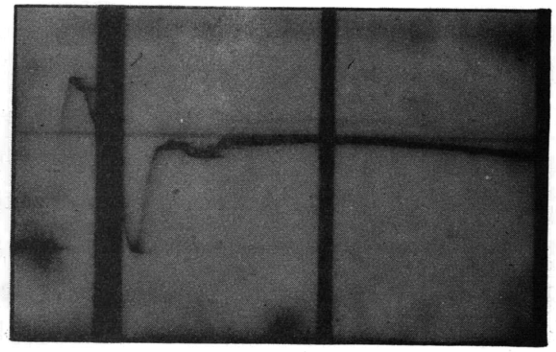
The velocity at the point of attachment of the velocity meter may be considered to include a component which is the mean velocity of the bar plus additional components due to the forced vibration of the bar in its various modes. Now all modes, except that mode which represents the mean translation of the bar, will induce transverse motions of the lateral surface. This will radiate energy into the water, and so the vibrational modes will decay in amplitude. However, there is no apparent mechanism for the translational velocity to decrease, except as a result of forces applied to the ends. Hence if the total velocity is recorded with a relatively slow-acting galvanometer, the contribution of the vibrational modes will eventually disappear, and the galvanometer will indicate only the mean velocity of the bar. Even if the higher modes were not attenuated as described, the galvanometer would attenuate their contribution to the velocity because of the low resonant frequency of the galvanometer.

The mean velocity of the bar should vary qualitatively as shown in Figure 2a. As the shock wave enters the bar, the mean velocity should rapidly increase and continue to increase until time T when the incident pressure is cut off by cavitation and the preceding impulse flux is trapped in the bar. During the cavitation phase, the forces acting on the bar are the air pressure from above, the tension in the supporting spring, and the weight of the bar. These should give the bar a constant deceleration. The descending portions of the oscillograms are assumed to be a record of the velocity during the later cavitation phase. The high-frequency oscillations which are superimposed upon this line of constant negative slope are presumably related to the longitudinal vibration of the bar.

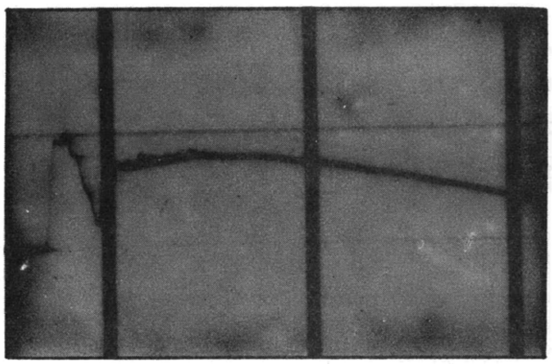
The galvanometer used for recording the signals from the velocity meter, as shown by the response to a step voltage in Figure 1, cannot reproduce faithfully the initial change in velocity. Its response time is about 1 msec, which is considerably greater than the time T



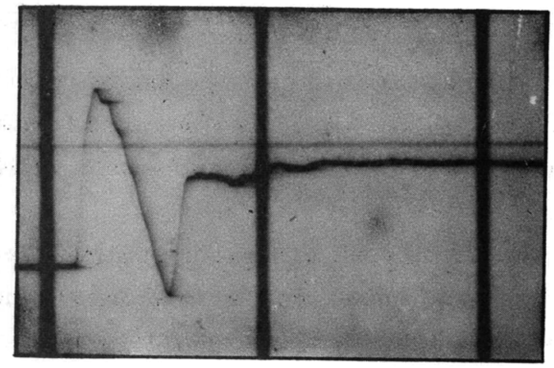
Army Engineers Special Blasting Cap (ES)
2.5 Ft below Bar



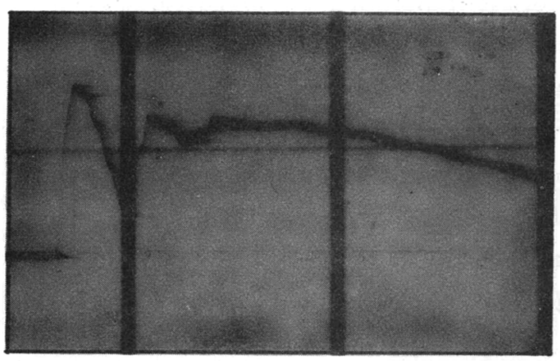
ES + 15 gm of Pentolite, 5 Ft below Bar



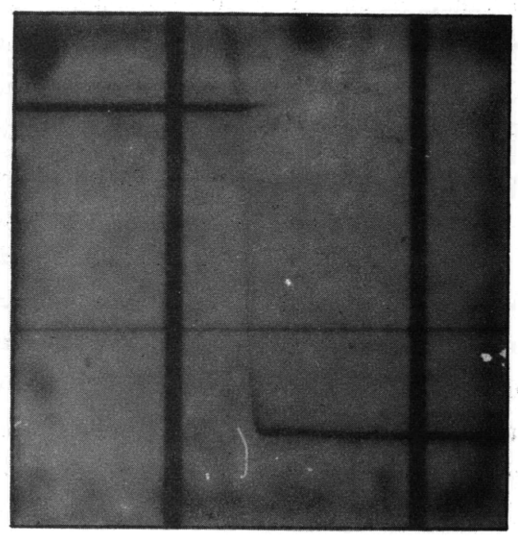
ES + 3 gm of Pentolite, 3.33 Ft below Bar



ES + 25 gm of Pentolite, 6.25 Ft below Bar



ES + 7 gm of Pentolite, 3.33 Ft below Bar



Step Voltage Applied to Galvanometer of Oscillograph

Figure 1 - Initial Part of Selected Velocity Traces for 12-Inch Bar and Calibration Step

The heavy vertical lines are 10 msec apart.

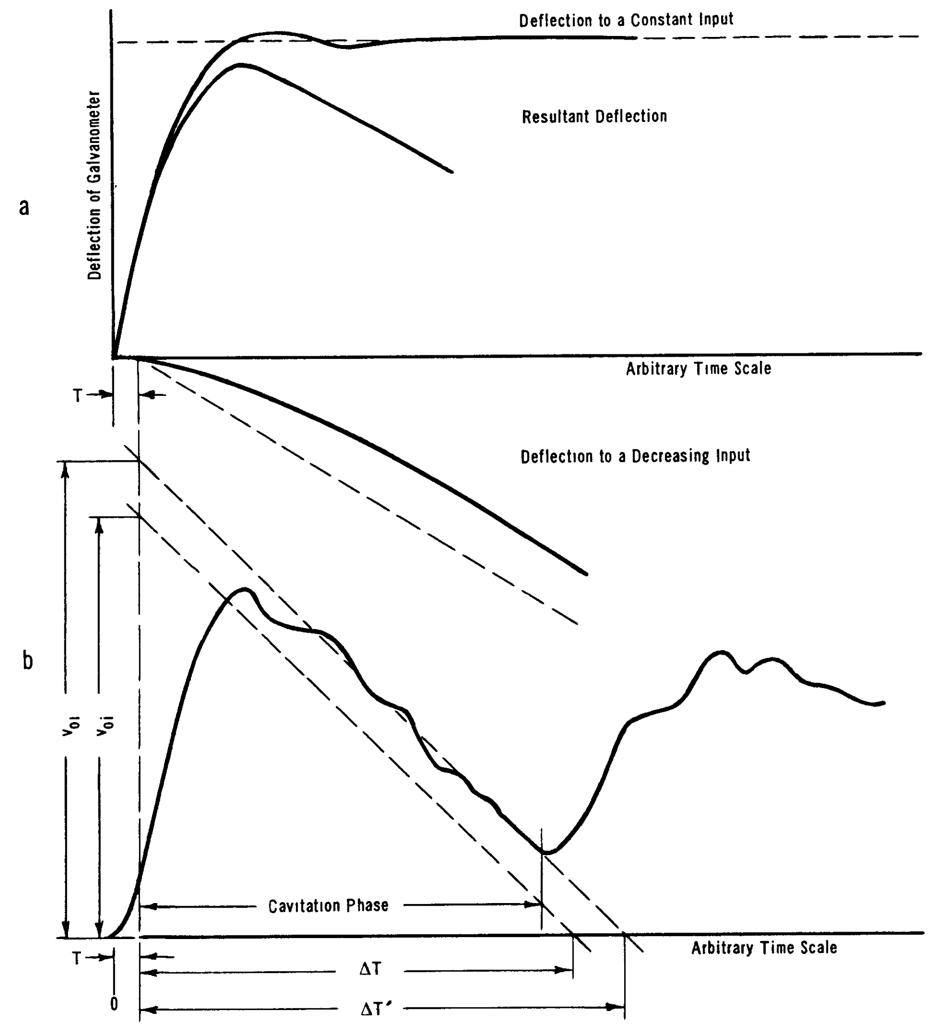


Figure 2 - Method of Evaluating the Initial Portion of the Velocity Trace

T is the transit time of the shock wave traveling through the bar up and down, $\Delta T'$ and v'_{oi} are read directly as shown, and ΔT and v_{oi} are computed. The diagram is not drawn to scale.

to cavitation. Accordingly the velocity trace in Figure 2 continues to rise during the interval of ballistic response of the galvanometer although cavitation should already be causing deceleration of the bar.

On the basis of the foregoing argument, the approximate mean velocity of the bar at time T is measured as shown in Figure 2b. A straight line is drawn through the descending trace of each record and extrapolated back to a time T after the start of the record. However, this extrapolated velocity v'_{oi} overestimates the true velocity because of the response characteristics of the galvanometer. The additional correction, as derived in the Appendix, depends upon the response of the galvanometer to a step input signal as in the last oscillogram of Figure 1. For the conditions of the tests, the correction amounted to 6 to 12 percent. The corrected velocity is v_{oi}.

In some tests, the velocity v'_{oi} was calculated from a measurement of the time $\Delta T'$, (Figure 2) which is the interval between T and the time at which the line of constant deceleration intersects the time axis where the target velocity is zero. This calculation does not require any knowledge of the sensitivity of the velocity meter or galvanometer, but it does assume that during the cavitation phase, the deceleration of the bar is constant and equal to

$$A = \frac{P_0 \pi r^2}{m}$$

where P_0 is the hydrostatic pressure on the bottom,

πr^2 is the cross-sectional area, and

m is the mass of the target.

The velocity is

$$v'_{oi} = \frac{P_0 \pi r^2}{m} \Delta T'$$

The same correction is necessary for galvanometer characteristics, as explained in the Appendix.

Consider now how these values of v_{oi} are related to the impulse of the shock wave.

The impulse of the shock wave per unit area in water up to a time T is

$$I_T = \int_0^T p \, dt$$

where p is the excess pressure above hydrostatic pressure. It is now assumed that this impulse varies according to the following simplified relation

$$I\left(\frac{T}{T_{m_1}}\right) = A\left(\frac{T}{T_{m_1}}\right)\frac{W^{2/3}}{D}$$

where T_{m_1} is half the first bubble period in sec,

W is the charge weight in lb,

D is the distance to the charge in ft, and

$A(T/T_{m_1})$ is a function of the proportionate time T/T_{m_1} and represents the impulse flux at a unit distance from a unit weight of charge.

The pressure, acting on a target with bottom area πr^2, mass m, and the same acoustical impedance as water, should cause the target to move with a mean velocity v_{oi} such that

$$m v_{oi} = \pi r^2 I_T = \pi r^2 \int_0^T p \, dt = \pi r^2 A \frac{W^{2/3}}{D}$$

From this it follows that

$$A\left(\frac{T}{T_{m_1}}\right) = \frac{Dmv_{oi}}{\pi r^2 W^{2/3}} \qquad [1]$$

Hence the reduced impulse $A(T/T_{m_1})$ can be computed from a measurement of the initial peak velocity v_{oi}.

There are several factors which may contribute to an error in the measurements and their interpretation. The velocity v_{oi} could be determined from the oscillograms with an uncertainty of 5 to 10 percent. The mass of the velocity meter coil was 0.03 slug. This was a large fraction of the total mass of the target, and its effect on the reflected shock wave in the bar has been ignored. Exact analysis is complicated because the coil covered only a part of the top surface of the bar. Also, it has been assumed that cavitation in the water occurs immediately upon application of a tension. It is recognized that a delay of as little as 5 or 10 μsec could permit a significant amount of the impulse to travel back into the water.

TEST RESULTS AND DISCUSSION

The measured values for the reduced impulse $A(T/T_{m_1})$ are listed in Table 2 together with the characteristic data for each test. T is taken as the transit time in the bar, which is equal to 2 l/c, where l is the length of the bar and c the velocity of sound in it. The values of $A(T/T_{m_1})$ are plotted in Figure 3 versus the proportionate time T/T_{m_1}. The points are experimental values. It can be seen that the experimental values tend to increase with increasing T/T_{m_1}. The proportionate impulse at $T/T_{m_1} = 0.0025$ is about 1.5 and increases to a value of about 4 at $T/T_{m_1} = 0.030$. At about 6.7 times the time constant θ of the shock wave, where $T/T_{m_1} \cong 0.0065$, the value for the impulse is about 2.25.

The experimental data from the tests are compared in Figure 3 with an independent calculation of the impulse. The solid curve represents the reduced impulse calculated under the assumption that the pressure at a point is due solely to the incompressive flow about the expanding gas bubble. In that case, the impulse at a distance D from the charge, where the particle velocity in the water is u, can be written

$$I = \rho D u = \frac{AW^{2/3}}{D}$$

and

$$A = \frac{\rho D^2 u}{W^{2/3}}$$

Now take D as the maximum radius of the bubble, where experimentally, at atmospheric pressure

$$R_m = JW^{1/3}$$

TABLE 2

Measured Reduced Initial Impulse Generated from Charges for Various Test Conditions

Length of Target in.	Mass of Target m slugs	Transit Time of Shock Wave in Target msec	Reduced Initial Impulse Generated From Charges				
			ES	ES + 3	ES + 7	ES+ 15	ES+ 25
30	0.0820	0.50	4.0	3.18	3.18	3.15	
27	0.0775	0.45	4.45	3.36	3.03	2.81	2.67
24	0.0695	0.40	3.60	3.12	2.80	2.67	2.53
21	0.067	0.35	3.65	3.04	2.77	2.66	2.62
18	0.063	0.30	3.30	2.84	2.60	2.45	2.38
15	0.0576	0.25	3.28	2.70	2.64	2.40	2.31
12	0.0532	0.20	3.08	2.70	2.35	2.25	2.06
9	0.0470	0.15	2.66	2.24	2.02	1.95	1.80
6	0.0420	0.10	2.20	1.97	1.90	1.63	1.50

The reduced impulse $A(T/T_{m_1}) = Dmv_{oi}/W^{2/3}\,\pi r^2$ where mv_{oi} is the initial momentum of the target and πr^2 is the area of the target bottom.

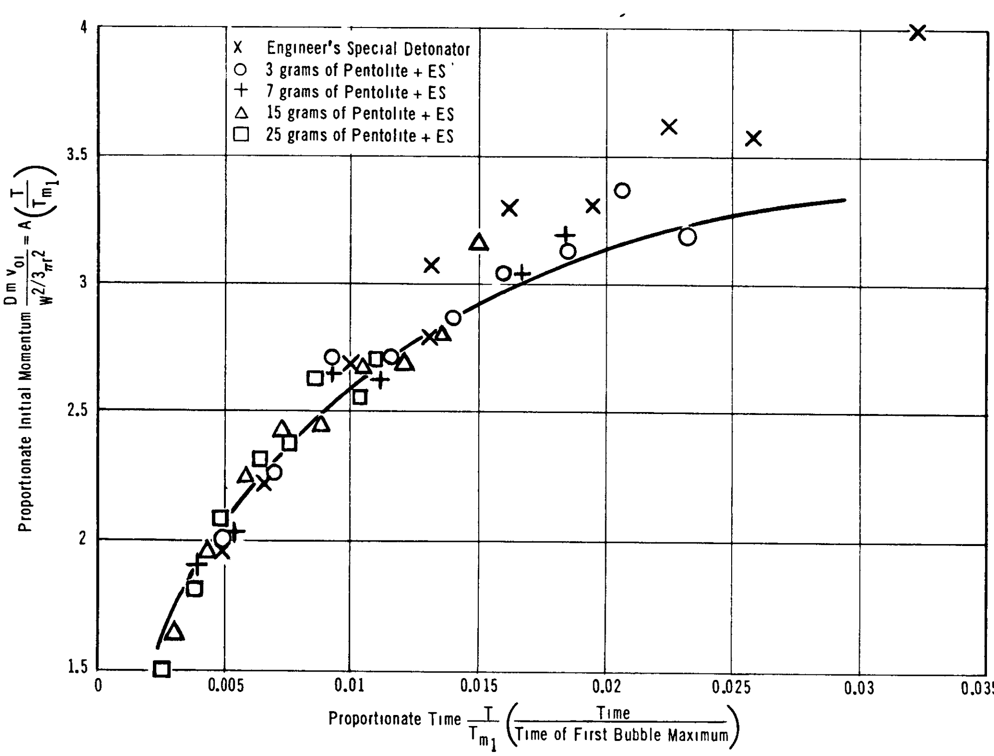


Figure 3 - Proportionate Initial Impulse Versus Proportionate Time for Indicated Charges

The curve is derived from particle velocity in free water for a hydrostatic pressure of 39 ft of water.

Hence

$$A = \rho J^2 u$$

where u is now the particle velocity at the distance R_m and time T/T_{m_1} and the charge is supposedly detonated at atmospheric pressure. If, however, the charge is detonated at a depth of H ft, the reduced impulse will be

$$A\left(\frac{T}{T_{m_1}}\right) = \rho J^2 \left(\frac{34}{H+34}\right)^{1/6} u\left(\frac{T}{T_{m_1}}\right) \qquad [2]$$

For this calculation, J was taken as 14.4, which is the value appropriate for small charges of pentolite at shallow depths.[1] The particle velocity u at $D = R_m$ was taken from the calculated values of Kennard which are reported in Reference 2, Table 1, and H was taken as 5 ft.

The most reliable of the experimental values in the tests described here are the smaller values of the proportionate impulse because these were obtained with the larger charges. These lower values agree with the calculations based on the particle velocity. At large proportionate times, the experimental values tend to be high in comparison with the calculated values.

The motion of a surface target after the cavitation is closed up was reported earlier.[1,2] It was shown that the target acquired a momentum equal to that of the displaced water. A calculation of the impulse from the particle motion of the water (i.e., by Equation [2]) was also made for a charge at a depth of 500 ft. The results showed agreement with the impulse curve published by Arons,[3] even down to values for $T/T_{m_1} = 0.003$.

All these results show a steady increase of the impulse in the water up to the end of the positive phase of the pressure at a time of about 0.1 bubble period. The final value of the impulse is largest at the surface and decreases with depth.[3] Based on the experimental results, a target near the surface may obtain a final vertical momentum more than twice as much as obtained by integrating the initial exponential part of the shock wave up to 6.7 times the time constant.

CONCLUSIONS

1. The impulse produced by an underwater explosion increases with time up to about 0.1 the bubble period and reaches values two or more times that contained in the initial exponential part of the shock wave.

2. The impulse measured by the wooden-bar technique at 6.7 times the time constant checks fairly well with reported values of the shock-wave impulse.

3. The initial momentum of a solid floating structure exposing the same area to a charge in a fixed position with respect to the bottom increases with increasing height.

ACKNOWLEDGMENTS

The tests were conducted at the test pond of the David Taylor Model Basin. Mr. John G. Batchelder assisted in conducting the tests and evaluating the results.

Dr. W.J. Sette and Dr. G. Chertock contributed valuable discussions and suggestions.

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APPENDIX

CORRECTION IN INITIAL PEAK VELOCITY DUE TO LAG OF THE MEASURING SYSTEM

The velocity input into the measuring system may be considered in a simplified way as shown in Figure 4a. The velocity increases initially to a peak value of v_1. After a time T, it decreases with a constant slope α due to the cavitation phase of the explosion phenomena, which may last up to a time $T + T_1$.

The output of the measuring system may be obtained by separating the input into two parts, A and B, which act simultaneously as shown in Figure 4b. A includes the initial input phase, and, after the time T, it remains at the constant value V_1. With the beginning of the cavitation phase, the total input steadily decreases by the amount shown in curve B.

The total response of the measuring system may likewise be separated into two parts which represent the response of the system to inputs A and B separately; see Figure 4c. Then the response v at a time $T + T_1$, where T_1 is reckoned from T and is supposed to be large compared with the response time of the system, is

$$v(T + T_1) = v_1 - \int_0^{T_1} \alpha y_0(t)\, dt$$

where $y_0(t)$ is the dimensionless output as a function of time to a unit velocity step (not shown in Figure 4).

The input at $T + T_1$ is $v_1 - \alpha T_1$. Hence the output exceeds the input at time T_1 by an amount

$$\alpha \left[T_1 - \int_0^{T_1} y_0(t)\, dt\right]$$

If the time T_1 is large enough, then the factor in parentheses is a constant value $c(D)$ for the damped galvanometer and may be obtained by integrating under the curve for the response to a unit step input. This difference will also occur in obtaining v_1 by extrapolating the portion of the record with constant slope back to time T. Hence the percentage error in determining v_1 by so extrapolating is

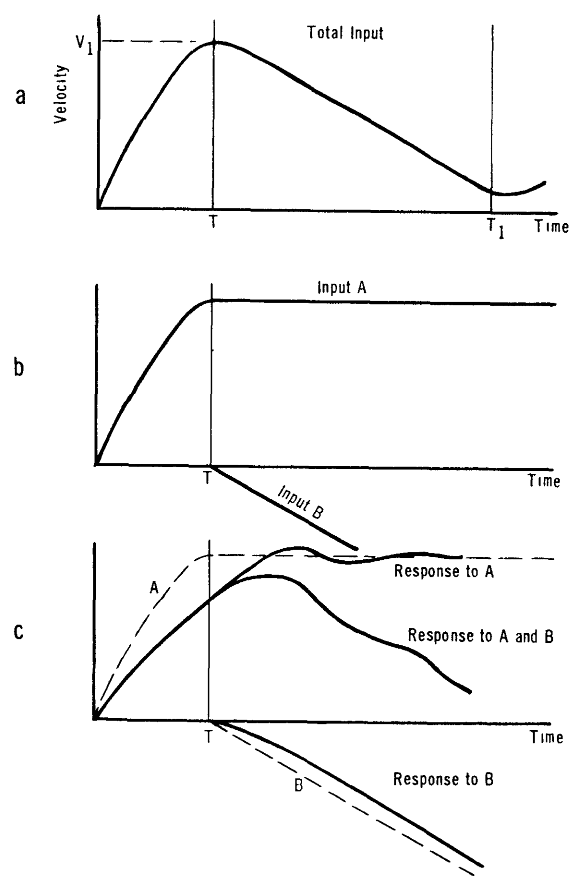

Figure 4 - Response of Measuring System to Input Velocities

$$\frac{\alpha\,[T_1 - \int_0^{T_1} y_0\,(t)\;dt]}{v_1}$$

If ΔT is the time from T to the time when the decreasing output crosses the zero line, we may replace v_1 by $\alpha\,\Delta T$ and obtain

$$\text{Percent error} = \frac{T_1 - \int_0^{T_1} y_0\,(t)\,dt}{\Delta T}$$

ΔT may be measured from the obtained output trace; see Figure 2.

The percent error may be expressed as $c\,(D)/\Delta T$ where $c(D)$ is a function of the damping. This error will decrease with increasing ΔT and increase with $c(D)$, which increases with damping of the galvanometer.

The correction for the tests described in this report varied from 6 to 16 percent.

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3	Dept of Aero Eng & Appl Mech, Polytechnic Inst of Brooklyn, Brooklyn, N.Y. 1 Prof N.J. Hoff 1 Prof P.G. Hodge 1 Prof. J. Kempner
1	Prof. W.H. Hoppmann, II, Dept of Mech Eng, Johns Hopkins Univ, Baltimore, Md.
1	Prof. M.C. Junger, Acoustics Lab, Harvard Univ, Cambridge, Mass.
1	Prof. H.L. Langham, Dept of Theo & Appl Mech, Univ of Illinois, Chicago, Ill.
1	Prof. N.M. Newmark, Dept of Civil Eng, Univ of Ill, Chicago, Ill.
1	Prof. E.H. Lee, Div of Appl Math, Brown Univ, Providence, R.I.
1	Prof. Paul M. Naghdi, Dept of Eng Mech, Univ of Michigan, Ann Arbor, Mich.
1	Prof. W.A. Nash, Dept of Eng Mech, Univ of Florida, Gainesville, Fla.
9	BJSM (NS)

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David W. Taylor Model Basin. Rept. 969.
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