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Defence Science Journal, Vol 46, No 1, January 1996, pp 9-13
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Conversion of Dynamic High Pressures from Air-to-Water for a Spherical TNT Charge

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ABSTRACT

A numerical method has been applied to convert the dynamic high pressures from air-to-water for a spherical TNT charge. Standard equation of scaling law in air for TNT has been utilised to make the necessary conversions. The investigations have been made by taking into consideration the ambient pressure values for the two media. The calculations have been performed under the scaled distances to get better results. Experimental measurements using indigenous blast pressure gauge have been undertaken by detonating spherical charges of TNT under the same scaled distances in water to check the correctness of results and direct application of this method. A fairly close agreement between the theoretically computed and the experimental values of the dynamic high pressures shows the practical utility of this approach in that it enables an estimate of the experimental shock wave pressures, without conducting underwater experiments.

1. INTRODUCTION

Sustained scientific efforts by several researchers have significantly contributed towards the basic theory and experimentation for free air as well as underwater conventional explosive detonations. Based on the theoretical and experimental observations, a number of model equations for scaling laws have been developed for different explosives. TNT, being one of the commonly used explosives with consistent behaviour, has been investigated thoroughly for its shock and detonation characteristics[1-4].

When an explosive is detonated in air, it is converted almost instantaneously into explosive gases which remain in the state of high pressure and temperature. The hot gases expand violently and force the surrounding air out of the volume it occupies. As a result of this a layer of compressed air, i.e., the explosive shock wave develops in front of the gases. This shock wave being transient in nature has a discontinuous pressure rise followed by an exponential decay. Practically all energy of chemical explosion is given to this spherically expanding explosive shock wave. The pressure of the explosive gases gradually decreases until it comes down to ambient pressure value. The shock wave, then no longer supported by the gas particles, tears off and continues to move independently. The development of shock wave in water is similar to that of an air explosion. But there is only a small quantitative difference. Owing to relatively higher pressure and weight of water, the main shock is followed by the bubble pressure pulses formed by the pulsation of product gas bubbles.

The present study is restricted only to the shock pressure phenomenon due to TNT explosive in the two media, i.e., air and water. Shock wave pressures have been calculated by incorporating the values of the local pressures of the medium in the standard equation of scaling law for TNT. The computed pressures from the scaling law have been compared with the experimental pressures generated by conducting dynamic measurements in air as well as in water.

2. EXPERIMENTAL DETAILS

Mild steel water tank of 6 m diameter and 6 m depth has been fabricated at the Terminal Ballistics Research

Received 23 August 1994, revised 24 April 1995

Laboratory (TBRL), Chandigarh, by using 20 mm thick mild steel plates supported by stiffeners to undertake experimental measurements in water with scaled down charges. One-third portion of the tank is embedded in the ground supported by concrete basement to enable it to withstand high pressures. The information regarding dimensions of the tank, field setup and method of measurement has been reported in our earlier publications[5-7]. Underwater pressure gauge having aerodynamic streamlined shape using quartz crystal as the sensing element has been designed and developed at TBRL to record the shock wave pressures in water[8]. The pressure transducer is positioned at a pre-determined distance from the point of explosion. The point of measurement and the point of explosion are suitably adjusted in the water tank to minimise reflections from the surface of water and sides and bottom of the tank. Figure 1 shows the typical instrumented pressure-time profile of underwater shock wave generated by spherical TNT charge weighing 0.115 kg and placed 0.5 m away from the gauge at a depth of 2.85 m in the water tank.

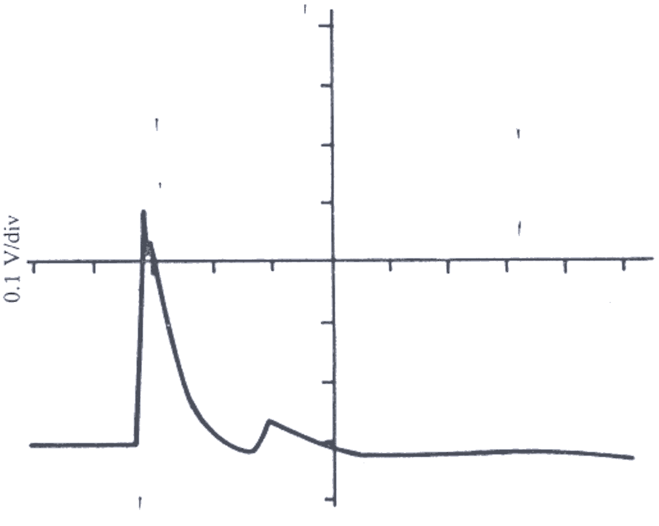

Figure 1. Pressure-time profile of shock wave in water.

Experimentally measured pressures under the same scaled distances by conducting free air measurements with spherical TNT charges weighing 3.41 kg by using imported H_3 blast pressure gauge have also been utilised to confirm the validity of conversion results in the reverse order, i.e., from water-to-air. The field setup and the technique for measurement of explosive pressures in air have been reported elsewhere[9,10]. Figure 2 gives the pictorial view of shock wave in air at a point other than the point of explosion after a time t, where P_1-P_0 is the peak pressure over atmosphere, τ the positive duration for which the blast wave exists. I the impulse measured by the area (shaded) under pressure-time curve, t the arrival time of the blast wave at that point from the point of explosion and τ' is the negative phase being formed due to rarefaction at the explosion point caused by the overexpansion of explosion gases. Blast gauge used for experimental measurements has, however, not been designed to record the negative phase of shock wave.

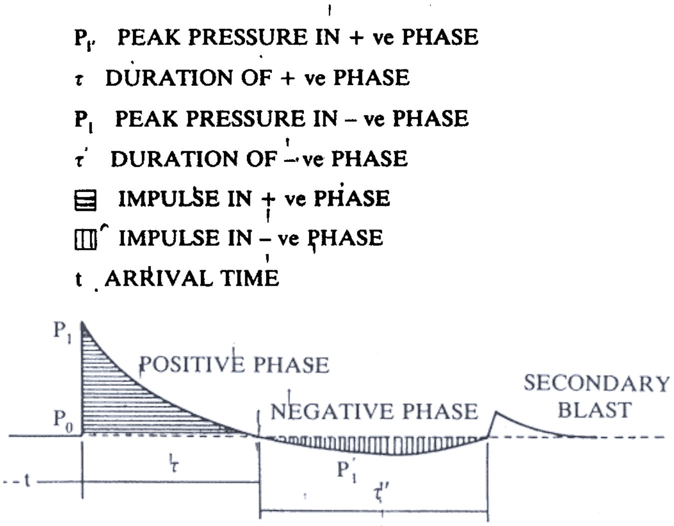

Figure 2. Pictorial view of shock wave in air.

3. THEORETICAL CONSIDERATIONS

After the explosion, the shock wave produced represents a thin spherical shell of energy. As the shock wave propagates outward from the point of explosion, it attenuates very rapidly and degenerates into a sound wave with further decrease of its pressure to an ambient value. The attenuation is due to the finite energy being distributed over an increased area and also its dissipation in transition through shock front. The shock wave obeys scaling laws, i.e., if the shock wave characteristics of an explosive in a medium, say air, are known, the shock wave parameters of the same explosive in the other medium, i.e., water, can be determined by making necessary substitutions of local pressures in the scaling law. Shock wave scaling law for TNT in air has been derived by Sadovskii[11] on the basis of theory of model similarity. The coefficients of the equation have been established experimentally to arrive at the following relationship:

$$P_s - P_o = \frac{0.76}{\bar{R}} + \frac{2.55}{\bar{R}^2} + \frac{6.5}{\bar{R}^3}\left(\mathrm{kg/cm^2}\right) \qquad (1)$$

$$1 \le \bar{R} \le 15 \ \mathrm{m\ kg^{-1/3}}$$

where $\bar{R} = R/W^{1/3}$ is the scaled distance, P_s the shock pressure, P_0 the atmospheric pressure in air, R the distance in metres and W is the charge weight in kg.

Neglecting P_0 in case of underwater shock, the above equation can be written as :

$$P_s = \frac{0.76}{\bar{R}} P_o'^{2/3} + \frac{2.55}{\bar{R}^2} P_o'^{1/3} + \frac{6.5}{\bar{R}^3}\left(\mathrm{kg/cm^2}\right) \qquad (2)$$

$$1 \le \bar{R} \le 15 \ \mathrm{m\ kg^{-1/3}}$$

where P_0' is the local pressure for water.

Based upon the cohesive forces of the medium, this standard equation of scaling law has been modified for water by making necessary conversions. The cohesive forces are the van der Waals forces of attraction existing between atoms and molecules of a substance. These forces arise as a result of electrons in the neighbouring atoms or molecules moving in sympathy with one another. They are responsible for the term a/v^2 in the van der Waals equation of state, which explains the behaviour of ideal gas equation more correctly. The elastic behaviour of any medium depends upon the strength of these van der Waals forces present in that medium. The van der Waals forces are very weak in air, whereas they are significantly strong in water. This is because water behaves as a highly elastic medium up to pressures of the order of several thousand kg/cm^2. Normally these pressures for water are taken to be 10 × 10^3–12 × 10^3 kg/cm^2. Taking P_0' equal to 10 × 10^3 kg/cm^2, Eqn (2) reduces to :

$$P_s = \frac{363.76}{\bar{R}} + \frac{53.28}{\bar{R}^2} + \frac{6.5}{\bar{R}^3}\left(\mathrm{kg/cm^2}\right) \qquad (3)$$

$$1 \le \bar{R} \le 15 \ \mathrm{m\ kg^{-1/3}}$$

Shock wave field of maximum stress for the explosion of TNT spherical charge in water has been investigated theoretically as well as experimentally by several research workers. Analysing the available results from theoretical and experimental observations the following relation has been obtained[11,12]:

$$P_s = \frac{355}{\bar{R}} + \frac{115}{\bar{R}^2} + \frac{2.44}{\bar{R}^3}\left(\mathrm{kg/cm^2}\right) \qquad (4)$$

$$0.05 \le \bar{R} \le 10 \ \mathrm{m\ kg}$$

Applying the conversion principle on this equation in the reverse order, it reduces to :

$$P_s = \frac{0.75}{\bar{R}} + \frac{5.50}{\bar{R}^2} + \frac{2.44}{\bar{R}^3}\left(\mathrm{kg/cm^2}\right) \qquad (5)$$

$$0.05 \le \bar{R} \le 10 \ \mathrm{m\ kg}$$

This is the scaling law for TNT spherical charge explosion in air under the given limits of scaled distance.

It is seen from the literature that $W^{1/3}$ scaling has been universally adopted for free air and underwater explosion studies[1,2]. In high explosive blast propagation problems, by applying similarity principles and dimensional analysis, $W^{1/3}$ scale factor for distances is obtained when elastic forces involved in the physical problem are considered. Gravity and viscous forces are neglected in the cube-root scaling analysis. Water being a heavy medium, gravitational effects are insignificant in it and also there is not much change in the viscosity value of sea water up to a certain depth. The conversion method used in the present paper is therefore applicable for a few hundred metre-deep explosions.

4. RESULTS AND DISCUSSION

Experimental data obtained at TBRL by detonating spherical charges of TNT in air as well as in water have been utilised for the analytical conversion of dynamic shock pressures in the two media. The conversion principle is significant from the point of view of knowing the apparent explosive pressures in advance without conducting experimental measurements. Based upon the experimental and the available theoretical observations, the scaling law for conversion of pressures from air to water has been determined and given in Eqn (3). The scaling law for conversion of explosive pressures from water to air has also been determined. This scaling law has been given in Eqn (5). The aim of the authors in this paper is to give information to the scientific community about the numerical assessment of underwater shock pressures without conducting experimental measurements in water. This is done by carrying out experiments in air and subsequent conversion of dynamic pressures from air to water using the conversion Eqn (3). A fairly close agreement between the experimental and computed shock pressure values (Table 1) shows the direct utility of this conversion method, particularly when immediate measurement of experimental pressures in water is not possible. The fabrication of shock pressure tank being costly and also in the event of this facility not being available at a particular site, the method will be very useful for theoretical determination of underwater shock pressures.

Table 1. Experimental and computed shock pressures for spherical TNT charge in water (charge weight = 0.115 kg)

Distance (m)	Scaled distance $\bar{R} = \frac{R}{W^{1/3}}$ (m. kg$^{-1/3}$)	Experimental shock pressure (kg/cm^2)	Computed shock pressure (kg/cm^2)
0.4	0.82	499.37	534.64
0.5	1.03	383.95	409.33
0.6	1.23	314.18	334.45
0.7	1.44	263.90	280.48
0.8	1.65	229.19	241.48
0.9	1.85	200.61	213.22
1.0	2.06	178.92	189.88
1.1	2.26	161.30	171.95
1.2	2.47	146.07	156.44

Table 2. Experimental and computed shock pressures for spherical TNT charge in air (charge weight = 3.41 kg)

Distance (m)	Scaled distance $\bar{R} = \frac{R}{W^{1/3}}$ (m. kg$^{-1/3}$)	Experimental shock pressure (kg/cm^2)	Computed shock pressure (kg/cm^2)
2.17	1.45	3.90	3.93
2.48	1.65	2.70	3.01
2.63	1.75	2.40	2.67
2.78	1.85	2.10	2.39
3.10	2.07	1.70	1.92
3.27	2.18	1.44	1.73
3.40	2.27	1.36	1.60
3.72	2.48	1.15	1.35
3.94	2.63	0.98	1.21
4.60	3.07	0.76	0.91
5.25	3.50	0.58	0.72

It may be mentioned here that the shock pressure measurements in air are cheap and easily possible without creating elaborate infrastructure. The conversion of pressures from water to air has been done only to check the validity of conversion results in the reverse order. The slightly higher percentage of variation between the experimental and computed results in this case (Table 2) indicates the need for further refinement in the substitution of local pressures and improving upon the scaling law given in Eqn (5). Efforts are being made in this regard while dealing with the blast behaviour of other explosives including that of TNT.

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