Underwater Explosion

1 Introduction

An underwater explosion is an explosion where the point of detonation is below the surface of the water.

Underwater explosion are categorized in accordance with their depth beneath the water's surface, because this has a strong influence on their effects. Below is an empirical criterion for shallow/deep underwater explosion (Le Méhauté and Wang, 1995):

$$\begin{cases} \dfrac{d}{W^{1/3}} < 1 & \text{shallow} \\ \dfrac{d}{W^{1/3}} > 16 & \text{deep} \end{cases}, \qquad (1)$$

where d is the explosive position relative to the free surface in feet, positive downward, and W is the yield of the explosive in pounds of TNT.

Note: TNT equivalent is a method of quantifying the energy released in explosions. The pound (or ton) of TNT is used as a unit of energy, approximately equivalent to the energy released in the detonation of this amount of TNT.

2 Deep underwater explosions

Figure 1 shows a typical deep underwater explosion. Compared with shallow underwater explosion, the heights of surface waves generated by deep underwater explosions are greater because more energy is delivered to the water. Deep underwater explosions are thus particularly able to damage coastal areas.

Figure 1. An example of a deep underwater explosion (from wikipedia).

Problem: In Figure 2, explosive of 55g RDX charge detonates at 3.5m deep. Is this a shallow/deep underwater explosion?

Solution:

Unit exchanges:

1kg = 2.2 lb
1meter = 3.28 ft

RDX has a TNT equivalent value of 170%. Therefore, The yield of the explosive in the experiment is

$$170\% \times 55 \text{ g} = 0.21 \text{ lb of TNT}.$$

Therefore, $W = 0.21$.

The explosive is placed about

$$3.5 \text{ meter} = 11.48 \text{ ft}$$

under the water level. Therefore, $d = 11.48$.

Since

$$\frac{d}{W^{1/3}} = \frac{11.48}{(0.21)^{1/3}} = 19,$$

this is a deep underwater explosion.

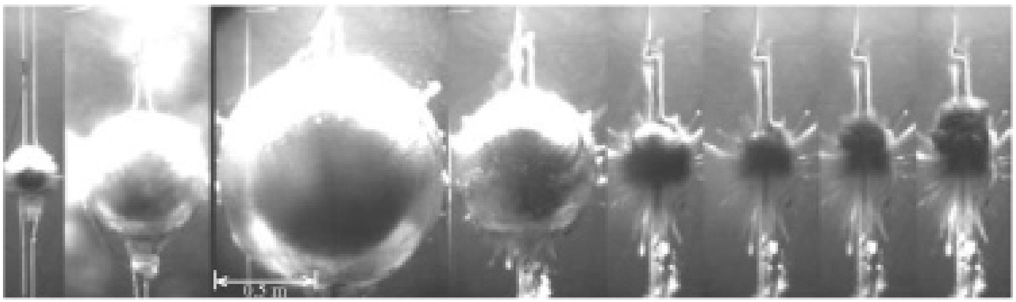

Figure 2. Explosion under free-field conditions: experimental results of a 55g explosive charge (RDX+wax); from left to right the bubble shape at: t =1, 7, 50, 85, 93, 94, 95 and *t*=96ms (from Klaseboer et al., 2005).

Experiment observation: free-field expansion

Figure 2 shows the observation of a free-field explosion. Free-field means that there is no immediate boundary (structures or surfaces) near to the explosion bubble. The image of the bubble in Figure 2 is the result of reflected light from the light sources in the set-up. The white vertical lines visible in Figure 2 are the supporting wires required to keep the charge in place before the explosion.

In Figure 2 the bubble grows to its maximum radius measuring 56cm at about *t*=50ms. The second minimum volume occurs at *t*=94ms.

Note: 1ms, 1millisecond, is 1 thousandth of a second.

Two phases' behaviour

An explosion is a chemical reaction in a substance that converts the original explosive material into a gas at very high temperature and pressure. In underwater explosion, the reacted gas sphere interacts with the surrounding fluid in two different phases.

The first is a transient shock wave, which causes a rapid rise in the fluid velocity, and large inertial loading. The peak pressure of this phase is very high, but its duration is extremely short.

The second phase in the explosion is a radial pulsation of the gas sphere. The water in the immediate region of the gas bubble has a large outward velocity and the diameter of the bubble increases rapidly. The expansion continues for a relatively long time, the internal gas pressure decreases gradually, but the motion persists because of the inertia of the outward flowing water. The gas pressure at later times falls below the equilibrium value determined by atmospheric plus hydrostatic pressures. The pressure defect brings the outward flow to a stop, and the boundary of the bubble begins to contract at an increasing rate. The inward motion continues until the inside compressed gas acts as a powerful check (stopper) to reverse the motion abruptly. The inertia of the water together with the elastic properties of the gas and water provide the necessary conditions for an oscillating system, and the bubble does in fact undergo repeated cycles of expansion and contraction.

In reality, oscillations of a physical bubble can persist for a number of cycles, ten or more such oscillations having been detected in favourable cases.

Pressure-time history

Figure 3 illustrates the pressure-time history, which is observed in the water at a fixed distance from the point of explosion.

- Upon arrival of the shock wave, the pressure rises instantaneously to the peak value and decreases at nearly exponential rate.
- Subsequent to the shock wave, other pressure pulses occur. These pulses arise from a much slower phenomenon, namely the pulsating of the gas bubble, which contains the gaseous products of the explosion.
- The high pressure of the gas causes an initially rapid expansion of the bubble and the inertia of the outward moving water carries it far beyond the point of pressure equilibrium.
- The outward motion stops only after the gas pressure has fallen substantially below the ambient pressure. Now the higher surrounding pressure reverses the motion.
- Again the flow overshoots the equilibrium and when the bubble reaches its minimum size, the gas is recompressed to a pressure of several hundred atmospheres. At this point we have effectively a second "explosion" and the whole process is repeated.
- The bubble oscillates in this way several times. The position and the size of the bubble are shown in Figure 3 for a few specific moments, which correspond to the pressure-time curve as indicated above.
- The pressure-time history reflects the low gas pressure during the phase where the bubble is large and it shows the pressure pulses, which are emitted from the bubble near its minimum.

- The period of the bubble pulsations is very long when compared with the shock wave portion of the pressure-time history of an explosion. In particular, this duration is long enough for gravity to become effective. Such a bubble has great buoyancy and, therefore, migrates upward. However, it does not float up like a balloon, but shoots up in jumps.

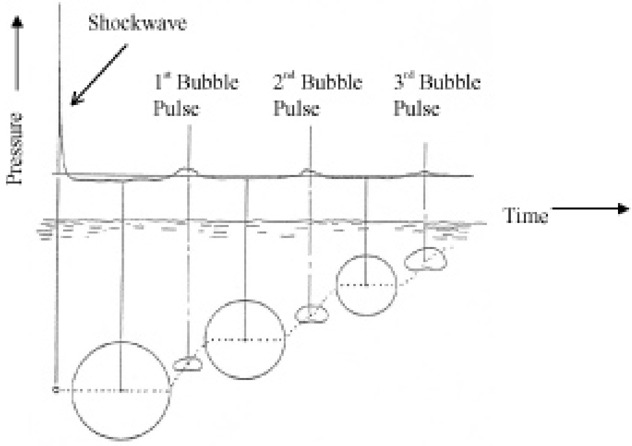

Figure 3. Pressure waves and bubble phenomena. (Snay 1956)

Bubble radius and oscillation period for the first cycle
The maximum bubble radius for the first cycle can be calculated as

$$R_{\max} = J\left(\frac{E}{P}\right)^{1/3}, \tag{2}$$

where P is the hydrostatic pressure at the burst point, E is the energy available for first cycle bubble motion; about half of the total explosion energy.

The oscillation period for the first cycle can be calculated as

$$T = K\frac{E^{1/3}}{P^{5/6}}\sqrt{\rho}, \tag{3}$$

where ρ is the density of water.

For underwater explosions at hydrostatic pressures of order 1~100 atmospheres, $J \approx 0.58$, $K \approx 1.12$.

Problem: Estimate the percentage of energy contribute to the bubble expansion for the underwater explosion experiment in Figure 2.

Solution:

For the experiment in Figure 2, the hydrostatic pressure at the burst point (3.5m under the water level) is

$$
\begin{aligned}
P &= \rho_{water} gh + 1atm \\
&= 1\times10^{3}\times9.8\times3.5\text{Pa} + 1.01\times10^{5}\text{Pa} . \\
&= 1.35\times10^{5}\text{Pa}
\end{aligned}
$$

Note: 1atm is the atmospheric pressure, which weights approximately $1.35\times10^{5}\text{Pa}$.

From Eq. (2), the energy can be estimated from the experimentally measured maximum bubble radius $R_{\max}$ as

$$E = \frac{R_{\max}^{3}}{J^{3}} P .$$

From experimental measured maximum bubble radius for the first cycle $R_{\max} = 0.56\text{m}$, the energy contributed to the first cycle bubble motion can be estimated as

$$
\begin{aligned}
E &= \frac{0.56^{3}}{0.58^{3}}\times1.35\times10^{5}\text{J} . \\
&= 1.2\times10^{5}\text{J}
\end{aligned}
$$

Explosive charge used is 55g RDX. RDX has a TNT equivalent value of 170%, and the energy available in the TNT is 1159cal/g. The unit exchange is $1\text{cal} = 4.184\text{J}$. Therefore, the total energy from detonation is

$$
\begin{aligned}
E_{\text{total}} &= 1159\times4.184\times55\times170\% J \\
&= 4.5\times10^{5} J
\end{aligned}
$$

The percentage of energy contribute to the bubble expansion is

$$E / E_{\text{total}} = \frac{1.2\times10^{5}}{4.5\times10^{5}} = 30\% .$$

In underwater explosion, energy is first transferred from the point of burst to the immediately adjacent water mass. In the underwater explosion shown in Figure 2, a strong shock wave which propagates away from the explosion point, carrying with it about 70% of the explosion energy, and leaving behind it a cavity (carrying with it about 30% of the explosion energy) which contains steam at high pressure. If the explosion is deep enough, this cavity, or "bubble," will grow in size. The internal pressure drops rapidly, to a maximum diameter determined by the explosion energy and the burst depth, and then collapse to a minimum size, re-expand, and continue to oscillate with decreasing amplitude and period.

Problem: Estimate the percentage of energy contributes to the bubble expansion for the underwater explosion experiment in Figure 2.

Solution:

The density of water is

$$\rho = 10^3 \,\mathrm{kg/m^3}$$

Using Eq. (3), the oscillation period for the first cycle can be estimated as

$$\begin{aligned} T &= K \frac{E^{1/3}}{P^{5/6}} \sqrt{\rho} \\ &= 1.12 \times \frac{\left(1.2 \times 10^5\right)^{1/3}}{\left(1.35 \times 10^5\right)^{5/6}} \sqrt{10^3}\, s\,, \\ &= 0.093 s \end{aligned}$$

which agrees with the experimental data (94ms).

3 Effects on nearby structure

The underwater detonation of an explosive can have serious effects on a nearby structure (such as a ship or submarine). The same amount of explosive can cause greater damage underwater than it would have caused in air, because water is much less compressible than air.

First damaging mechanism (high pressure)
Just after the detonation, a shock wave and an expanding high-pressure gas bubble will appear. This shock wave moves at a very high speed and will generate a very high pressure. When it hits the structure, it gives rise to the first damaging mechanism.

Second damaging mechanism (whipping effect)
While the pressure loading due to the shock impact can be very high, the duration is usually very short compared with the dynamics of the bubble. The explosive products form a high-pressure gas bubble and this bubble expands owing to the high pressure. However, inertia causes the bubble to over-expand and the pressure inside the bubble becomes lower than the surrounding reference pressure; it then stops expanding (for example, the maximum bubble diameter in a typical explosion of a torpedo of 500 kg TNT is of the order of 10 to 20m). The hydrostatic pressure is now larger than the pressure inside the bubble and a collapse phase will follow. If the frequency of the bubble 'matches' the eigen-frequency of the structure, it can lead to the so-called 'whipping' effect which can potentially constitute the second damaging mechanism.

Third damaging mechanism (jet impact)
In most cases, in the collapse phase, the attraction of the bubble towards the structure, the influence of gravity and inertia will cause a high-speed water jet to develop. The jet traverses the bubble and impacts on the other side of the bubble surface. This jet can be directed towards the structure and is then associated with a third damaging mechanism.

Rebound cycle

After jet impact, the bubble will become toroidal in shape and will continue to contract. Not long after the jet impact, the bubble reaches its minimum volume and a high-pressure peak can be observed. The bubble will then rebound again for a second cycle. It will have lost much of its energy and the second cycle is less 'violent'.

Problem: Describe the shock experienced by a naval target from an underwater explosion. *W* is the explosive charge.

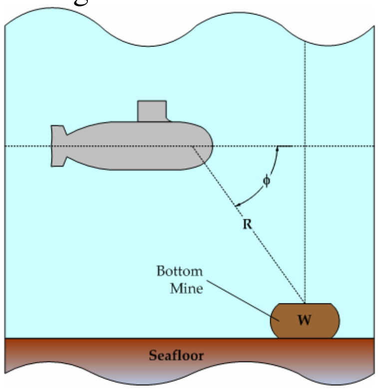

Figure 4. Underwater explosion scenario.

Solution:

An explosion close to a ship generates a shock wave that can impart sudden vertical motions to a ship's hull and internal systems.

The explosion also generates a gas bubble that undergoes expansion and contraction cycles. These cycles can introduce violent vibrations into a hull, generating structural damage, even to the point of breaking the ship's keel. Many of the internal mechanical systems (e.g. engine coupling to prop) require precise alignment in order to operate. These vibrations upset these critical alignments and render these systems inoperative. The vibrations can also destroy lighting and electrical components, such as relays.

References

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