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Underwater explosion induced shock loading of structures: Influence of water depth, salinity and temperature

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ABSTRACT

Most of the literature available for determination of the response of underwater explosion induced shock loading on structures considers free surface of water, no salinity in the water and also no special effects of initial temperature and latitude. Thereby question naturally arises as to whether these theoretical researches can directly be applied to practical situations in various seas/oceans around the world. A framework is prescribed in this manuscript through which designers can evaluate coefficient of reflection, a major factor for design of marine vessels and offshore structures for protection against blast loads, in different conditions considering water depth, salinity, temperature and also latitude. The manuscript illustrates variability in response with discussion of some idealized cases.

1. Introduction

High-intensity non-contact underwater explosion induced shock response of structures is primarily important for naval defense as well as for oil industries. Typically underwater mines are present at a depth of around 40 m below the surface. However nuclear explosions can even occur at 1 km below the water surface. Apart from warfare considerations, in days of increased terrorist activities throughout the world and the presence of deep submersible oil platforms in various places around the world (having different salinities and temperatures) it is important to determine the response of these structures under a probable underwater explosion induced shock wave. In general, there exists few published literature in the area of underwater explosion induced shock loads (Taylor and Batchelor, 1963; Cole, 1948; Penny and Dasgupta, 1942; Liu and Young, 2008; Ghoshal and Mitra, 2012). However, results obtained from these theories typically focus on effects obtained in surface or shallow or littoral waters (where the initial density and sound speed of water is taken at atmospheric pressure). The effect of salinity and temperature has also not been dealt within these prescribed theories. Typically an increase in depth of water results in an increase in hydrostatic pressure and also thereby a change in sound speed and density of the medium. Apart from that the temperature and the salinity of the water also change with depth and due to the location (latitude and longitude) of the water medium in earth. Thereby results obtained from the previous theories should be revisited considering the above mentioned facts.

To the best of the author's knowledge, there exist only two papers focussing on explosion loading in deep underwater. These previous literatures (Schiffer and Tagarielli, 2012; Schiffer et al., 2012) report that the phenomenon of cavitation occurs at a distance away from the structure and not on the structure; however, both these studies consider the effect of underwater medium to be acoustic in nature. These two papers also do not consider the issue of explosion induced shock wave loading of structures. It has been pointed out by Ridah (1988) that nonlinear compressibility effects in water should be considered for high speed water jets with particle velocities in the range of around 1 km/s. The particle velocity in a TNT or RDX explosion is in the range of $3-7$ km/s (Cooper, 1997) which is significantly higher than that observed in high pressure water jets. Hence it may not be logical to consider the effects of acoustic medium for underwater explosions, as has been demonstrated by Ghoshal and Mitra (2012), but instead an assumption of nonlinear compressible medium should be considered in events of high-intensity underwater explosions. Moreover, it has also been previously pointed out in the literature that for a peak reflected pressure of 1000 bar, water medium can no longer be considered as acoustic and nonlinear compressibility should be taken into account (Cole, 1948). Penny and Dasgupta

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(1942) utilized Tait equation of state for water to predict the reflection coefficient during the study of underwater shock wave reflection from rigid wall. However, these studies including those of nonlinear compressibility by the authors, Ghoshal and Mitra (2012), do not consider the aspect of deep waters and the possible variations due to salinity and temperature which this manuscript strives to explore.

One of the major governing parameters considered in design of underwater structures against explosion induced shock-loading is coefficient of reflection (C_R) i.e. the ratio of the reflected pressure to the incident pressure pulse. The major objective in this research is to determine the change in C_R values for underwater explosions for deep-water situations in which along with the effect of depth there may be variations as a result of salinity and temperature. Typically, as per theory developed by Taylor and Batchelor (1963) and based on which almost all explosion resistant structures are designed, consideration of an acoustic medium in shallow waters (for which the incident peak over-pressure is taken to be the atmospheric pressure) limits the value of reflection coefficient to 2. However this upper bound value of reflection coefficient may not be true for high-intensity underwater explosion induced shock loading situations, which this manuscript strives to address. In this regard, it should be pointed out that proper selection of equation of state is necessary in consideration of nonlinear compressible medium for explosive events which in-turn specifically depends on the physics of explosion in the medium; as has been demonstrated for air medium by Ghoshal and Mitra (2015).

Since it is known that an increase in water depth not only causes a rise in hydrostatic pressure but also a variation in sound speed and density, there have been attempts by researchers to propose empirical formulae to calculate sound speed in water based on experimental results carried out at different locations on earth (Medwin, 1975; Mackenzie, 1981; Wong and Zhu, 1995; Leroy and Parthiot, 1998). One of the most recent empirical formulas valid for all ocean across the world has been proposed by Leroy et al. (2008) taking into account the effect of salinity, depth of water, temperature, and also the latitude. Empirical equations to calculate the density of sea water as a function of salinity, depth and temperature have been provided by Millero et al. (1980) and Fofonoff and Millard (1983). Nagayama et al. (2005) carried out experimentation on saline water to find the Hugoniot shock compression curve below 1 GPa. They also showed that there is an increase in the intercept values of the shock particle velocity curve (whose value is typically close to the sound speed in the medium) which corresponds to an increase in the sound speed whereas the slope of the compression curve remains unchanged.

In the present paper, a parametric investigation is done to study the influence of salinity, water depth, ocean temperature, etc. on underwater explosion induced shock wave phenomena in an open sea environment and subsequently on the loading of offshore structures. The paper is organized as follows: in Section 2 background theories for the development of analytical formulations are presented. Analytical formulations to predict the key parameter i.e., reflection coefficient, in determining the load on an offshore structure due to underwater explosion induced shock load, is presented in Section 3. Section 4 contains results along with their discussions. Finally in Section 5 conclusions are given.

2. Theoretical background

The objective of the present paper is to develop an analytical formula to determine the reflection coefficient for a structure subjected to underwater explosion induced shock in an open sea environment considering the influences of water depth, salinity and temperature. In this regard jump conditions are solved along with the equation of state for sea water. Background theories and formulation for jump condition, equation of state and empirical formulas for modeling sea water are presented in the following sections.

2.1. Rankine–Hugoniot jump condition

In literature, discontinuous form of the Euler equations (which considers medium to be inviscid) are typically referred as Rankine–Hugoniot jump (RHJ) conditions. In this analysis, direction of shock wave propagation is normal to the upstream flow direction. Therefore RHJ equations obtained are as follows for one-dimensional inviscid normal shock wave propagation.

Mass conservation gives

$$U_i\rho_i = \rho_j U_j. \tag{1}$$

Momentum conservation gives

$$(\rho_i U_i^2 + p_i) = (\rho_j U_j^2 + p_j). \tag{2}$$

Energy conservation gives

$$e_i + \frac{p_i}{\rho_i} + \frac{U_i^2}{2} = e_j + \frac{p_j}{\rho_j} + \frac{U_j^2}{2}. \tag{3}$$

Here U represents shock velocity measured with respect to reference frame attached to the shock front; sometimes called as stationary shock velocity or in other words spatial shock velocity. Flow state ahead and behind the shock are represented by index i and j respectively. Internal energy, pressure and fluid density are symbolized by e, p, and ρ respectively. To solve these jump conditions another equation is required i.e. equation of state which is described next.

2.2. Mie–Grüneisen equation of state

An equation of state (EOS) is an empirical relation for pressure (p) as a function of two or more thermodynamic state variable, $p = p(\rho, e)$. In the present work, the Mie–Grüneisen equation of state (EOS) is used for modeling the nonlinear compressible water medium. The expression for compression phase of Mie–Grüneisen EOS is given as

$$p = \frac{\rho_0 c_0^2 \mu\left[1 + \left(1 - \frac{\Gamma_0}{2}\right)\mu\right]}{\left[1 - (S_1 - 1)\mu\right]^2} + \Gamma_0\rho_0 e, \quad \text{if}\mu > 0, \tag{4}$$

where $\mu = \frac{\rho}{\rho_0} - 1$, ρ_0 is the density of the initial state, ρ is the current density, c_0 is the sound speed in water medium and S_1 is a fitting coefficient. Γ_0 is the Grüneisen parameter at initial state. The Grüneisen parameter (Γ) at any state can be obtained from the relation, $\Gamma_0\rho_0 = \Gamma\rho$.

Mie–Grüneisen EOS is developed based on experimentally determined Hugoniot curve which refers to the plot of shock velocity (U_s) vs. particle velocity (u_p). In the present work, the shock particle velocity relation provided by Bogdanov and Rybakov (1992) is used. This shock-particle velocity ($U_s - u_p$) relation consists of three discrete linear segments and considers the effect of phase change of water at high pressure. However for the present work only Phase I is considered, since phase transitions of water in an open-sea environment are yet to be reported. It should be noted that phase transition of water has been reported in laboratory based experiments (Bogdanov and Rybakov, 1992; Rybakov, 1996; Nagayama et al., 2002) and/or through numerical studies (Neogi and Mitra, 2016). This limits the applicability of present theory to a value of reflected over-pressure below 2.1 GPa.

The linear shock particle velocity relation is given as