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Experimental verification of different analytical approaches for estimating underwater explosives

Piotr Nowak[1], Tomasz Gajewski[2], Piotr Peksa[2] and Piotr W. Sielicki[2]

[1]Doctoral School, Institute of Structural Analysis, Poznan University of Technology, e-mail: piotr.nowaki@doctorate.put.poznan.pl
[2]Institute of Structural Analysis, Poznan University of Technology, e-mail: tomasz.gajewski@put.poznan.pl, piotr.sielicki@put.poznan.pl

ABSTRACT: The clearance of underwater ordnance is one of the most complex tasks entrusted to appropriately trained and equipped soldiers. State-of-the-art knowledge in this area is rarely published and is most often possessed by a narrow group of navy specialists. The aim of this paper was to find a link between the existing mathematical models for the peak pressure of underwater explosion (UNDEX) with measurements of small charge detonations for long ranges to the observation point in real life scenarios. We have shown the results of the research, in which the underwater explosion tests were presented for different TNT equivalents and standoff distances and thus distance ratios. The curves of pressure vs. time of ignition were reported. The measurements were confronted with empirical formulas. The comparison showed large, but expected, differences, since the empirical formulas are advised for smaller distance ratios. Based on the conclusions from the study, the new methodology to identify the loading from underwater explosions was postulated.

KEYWORDS: underwater explosion, experimental mechanics, analytical approach, blast wave, pressure impulse curve, similarity law

1. Introduction

From the military perspective the clearance of underwater ordnance (UXO) is one of the most important and complex tasks entrusted to appropriately trained and equipped specialists. As a result of the UXO detonation a bubble pulse is generated that transmits the energy of the explosive material through water in the form of a shock wave.

The commonly used parameters of the explosion are: the peak pressure, the shock wave impulse and energy, and the time constant. Although all explosion parameters can be calculated with the use of experimental formulas and factors, they apply to specific outside conditions and restrictions. Those conditions of the underwater explosions in real life scenarios are hard to follow, especially in the Baltic Sea in terms of charge weight and water depth limitations.

The original test configuration and environmental conditions of historical detonations were often not described in scientific publications, nevertheless they had a great impact on the final form of the mathematical equation. For instance, measurements in the shallow seas at long distances to the observation point are not in line with the predicted detonation parameters.

During historical experiments a short distance from the gauge to the center of the explosive charge was used when conducting measurements [1-5]. After numerous tests, the mathematical equations were introduced to calculate the parameters of the shock wave. The pressure data for a chosen energetic material can be predicted in specific conditions and standoffs to the observation point with the help of empirical formulas, for which the range of validity can be expressed in a nondimensional number of charge radii.

This study focuses on the measuring methodology of explosive events at shallow depth areas, such as the Baltic Sea. The new method proposed is to record low shock wave parameters with sensitive sensors at very long distances and to find a constant dependence on basic empirical formulas. This approach would allow us to approximate the outcome pressure parameters based only on depth and distance from the explosion with a limited number of detonation data, and correct geometric scaling of the charges and distances.

2. Materials and methods

The complex nature of the underwater detonation of condensed, high-energy explosives makes predicting its outcome a challenge for engineers. The motion of the water is partially responsible for the change of the pressure inside a gas bubble, producing pressure smaller than the hydrostatic value. This water nature pushed engineers to make many simplifications for the rapid assessment e.g., of the average loading data and pressure.

$$p(t) = p_m e^{-\frac{t}{\theta}} \tag{1}$$

To compare the recorded pressure parameters of a wide range of UNDEX tests, a reduced distance ratio $\bar{R}$ is used as a function of charge radius, assuming its an equivalent spherical charge, and a standoff distance:

$$\bar{R} = \frac{R}{r_o}, \tag{2}$$

R – distance to the observation point, [m]
r_o – spherical charge radius, [m]
As the radius depend upon the density ϱ of the explosive charge, the r_o is given by:

$$r_o = \left(\frac{3G}{4\Pi\varrho}\right)^{\frac{1}{3}} \tag{3}$$

The scheme of the test setup of underwater detonations conducted is presented in Fig. 1. The distance of the explosive to the pressure gauge is described by R. What is important, the depth of the water, h, was similar for both locations, i.e., mooring buoys “A” and mooring buoys “B”.

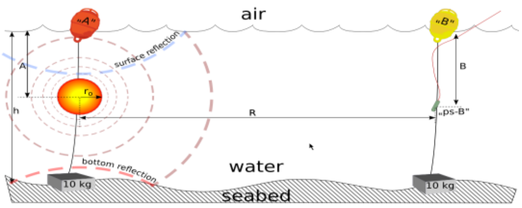

Fig. 1. Test setup of underwater detonations conducted

In the study, a series of 11 underwater detonations were conducted with the explosive mass varying from 4 to 8 kg. TNT explosives were used, mostly formed in the cuboidal charges. The distances from the center of the explosives charge to the pressure sensor were between 150 and 500 m. The tourmaline-ICP® pressure sensor (“ps-B”) was secured at the altitude of 8 m. The sensor properties ensured the accuracy of the pressure results below 1 kPa and registration with a 1e-6 s frequency. The tests were divided in five groups in regard to charge weight and distance ratio R/r_o.

3. Results and discussions

The goal of the experiment was to gather pressure data from UNDEX with a minimum influence on the Navy Divers training in the shallow regions of the Baltic Sea. The time axes have a value of 0 in the moment of detonation. The explosion generates a rapid pressure rise to a peak pressure p_m which is the most valuable measurement of the shock wave in the shallow depths. The maximum pressure measurements for all 11 UNDEX tests are presented in regard to empirical formulas of R. Cole and R. Koul (Fig. 2).

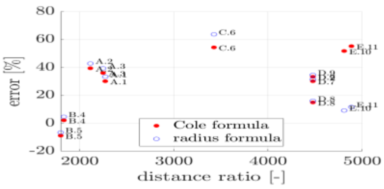

Fig. 2. Plot of the error of maximal pressure estimation due to empirical formulas [1, 6] to the experiment's outcome

The initial setup of the experiment in real life training can influence the registered parameters of the shock wave. The limitation of accepted mathematical models refers to conditions under which the measurements in the open sea can be applicable. The reflection of the pressure wave of the surface and sea floor can change the expected pressure values of the explosion in the observation point for ranges above 1000 charge radii, although good coverage with mathematical formulas was observed at distances around 1800 charge radius, which was considered in our study.

The pressure changes in time for the first impulse test no. 1 and 5 are shown in Fig. 3. For both cases the standoffs ratio was close to around 2000. The zoom-in of peak pressure values confirms the measurement quality. It reflects each measurement with microsecond accuracy (1e-6 s).

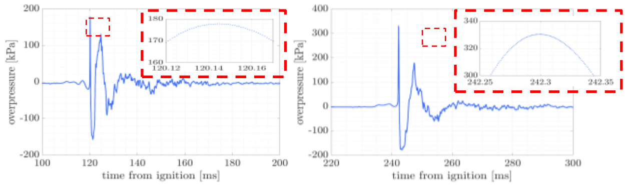

Fig. 3. Zoomed plots of selected overpressures from underwater detonations conducted: 1 and 5

The shallow depth conditions and long distance to the observation point are not an optimal setup for most of the underwater experiments but will have great economic advantages. The time factor and possibility to register UNDEX events outside the hazardous zone (Fig. 4) without any special preparation makes “the proposed survey methodology” ideal for military application especially during mine countermeasure operations (MCM). A database of detonation parameters for specific explosive quantities at the depth from 10-20 m will help to identify the explosive hazard in the area of operation.

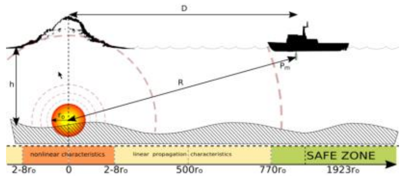

Fig. 4. Concept of measurement of the explosive event

4. Conclusions

The experimental measurement of parameters of an UNDEX is a very expensive and time-consuming process [1,5,7]. Most of the commonly used mathematical models, empirical as well as computational fluid dynamics approaches, are referring to specific conditions and outside parameters. The biggest disadvantage of those methods is the use a large mass of explosive with a small distance ratio.

The proposed method would require the use of small explosive charges at larger distances where maximum pressure of a few hundred kilopascals is registered. This setup would be easy to implement in the duties of the vessel crew close to an underwater minefield in combat situations. With the proposed method a large database of explosive events can be obtained during normal Navy training in the Baltic Sea. This data could be useful in combat to calculate the amount of explosive and identify the type of sea mines.

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