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Estimating depth and explosive charge weight for an extremely shallow underwater explosion of the ROKS Cheonan sinking in the Yellow Sea

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HIGHLIGHTS

- We derive cutoff frequencies of normal mode from bottom and surface reflection in shallow sea water.
- We estimate a detonation depth of UWE and ocean depth with cutoff frequencies.
- We confirm a detonation depth and the surface channel of this study based on ray-trace modeling.
- We corroborate the bubble pulse period using boundary element method (BEM).
- ROKS Cheonan UWE is due to a 136 kg TNT at a depth 8 m within a sea depth of 44 m.

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ABSTRACT

We estimated the detonation depth and net explosive weight for a very shallow underwater explosion using cutoff frequencies and spectral analysis. With detonation depth and a bubble pulse the net explosive weight for a shallow underwater explosion could simply be determined. The ray trace modeling confirms the detonation depth as a source of the hydroacoustic wave propagation in a shallow channel. We found cutoff frequencies of the reflection off the ocean bottom to be 8.5 Hz, 25 Hz, and 43 Hz while the cutoff frequency of the reflection off the free surface to be 45 Hz including 1.01 Hz for the bubble pulse, and also found the cutoff frequency of surface reflection to well fit the ray-trace modeling. We also attempted to corroborate our findings using a 3D bubble shape modeling and boundary element method. Our findings led us

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to the net explosive weight of the underwater explosion offshore of Baengnyeong-do for the ROKS Cheonan sinking to be approximately 136 kg TNT at a depth of about 8 m within an ocean depth of around 44 m.

1. Introduction

The underwater explosion (UWE) vis-à-vis the ROKS Cheonan took place off the coast of Baengnyeong Island in the Yellow Sea of the Korean peninsula on March 26, 2010 (see Fig. 1). Considerable efforts have been devoted to estimate the net explosive weight of this UWE using spectral analysis and analytical approach including simulation of boundary element method (BEM) (Kim and Gitterman, 2013; Kim, 2013). These attempts have typically used *ad hoc* models of the relationship between bubble pulse period and net explosive weight or have been based on 3D shape simulation by boundary element method (BEM). We attempted to estimate and interpret the source depth and a net explosive weight using underwater acoustics (hydroacoustics) as well as hydrodynamics. This paper, especially, presents the relationship between the cutoff frequencies and the detonation depth resulting in obtaining the net explosive weight, including application of ray-trace modeling for confirmation of estimation. We utilized cutoff frequencies to estimate the detonation and ocean depths including the bubble pulse period for the extrapolated net explosive weight. We also verified whether our estimated source depth fitted the observed one using ray-trace model in the shallow channel. The compelling reason of this study is to estimate the net explosive weight (NEW) for a very shallow underwater explosion (<50 m) using only cutoff frequencies and Rayleigh–Willis equation (Kim and Gitterman, 2013). The NEW estimation is possible using a cutoff frequency and the bubble pulse period from spectral analysis relating to the Rayleigh–Willis equation since it is a function of detonation depth and NEW.

2. Cutoff frequencies and normal modes for a shallow underwater explosion

Shallow water (<200 m) sound fields are defined in terms of a normal mode propagation which oscillates with resonant frequencies in series of harmonics. The normal mode propagation without attenuation are those for which water depth is greater than one-quarter wavelength ($H > \lambda/4$, $H =$ water depth, $\lambda =$ wavelength). The frequency corresponding to $H = \lambda/4$ is termed the cutoff frequency of the waveguide (as the critical frequency to build a waveguide). Waves with frequencies lower than the cutoff frequency are propagated in the channel only with attenuation and are not effectively trapped in the duct of the layer. There is no mode propagation below the cutoff frequency.

Note Snell's law from fundamental physics: $C_2 \sin\theta_1 = C_1 \sin\theta_2$ (C_1 and C_2 are velocity of upper layer and lower layer respectively and θ_1 and θ_2 are angle of incidence and transmission respectively). Taking one particular incident angle θ_C called a critical angle which is the transmission limit angle (90°), when the incident angle is greater than θ_C, all the incident waves are reflected in the water layer and no energy is transmitted in the sediment layer (Nicolas et al., 2003). The velocity with which the wave front progresses is dependent on the incident angle θ_1 and will always be greater than the medium velocity C_1 of each downward or upward ray. To focus on the critical angle $\theta_C = \theta_1$, the cutoff frequency (critical frequency) for each mode is simplified. If the incident angle is greater than the critical angle, the normal mode propagation starts in a waveguide. The wave propagates by multiple reflections at an incident angle between the grazing angle and critical angle for total reflection under the condition of constructive interference in the reflection off the ocean bottom (Nicolas et al., 2003) in case of $C_1 < C_2$.

According to Urick (1983), the cutoff frequency (critical frequency) for ocean depth (H) is presented as follow:

$$f_H = C_1(2n-1)/4H[1-(C_1/C_2)^2]^{-1/2} \quad n = 1, 2, \ldots \tag{1}$$