Peak sound pressure and sound exposure level from underwater explosions in shallow water

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Abstract: Experimental measurements of the peak pressure and sound exposure level (SEL) from underwater explosions collected 7 km off the coast of Virginia Beach, Virginia are presented. The peak pressures are compared to results from previous studies and a semi-empirical equation that is a function of measurement range and charge weight, and are found to be in good agreement. An empirical equation for SEL that similarly employs a scaling approach involving charge weight and range is also presented and shows promise for the prediction of SEL in shallow water.

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1. Introduction

As a result of experimental measurements emerging from World War II, a semi-empirical equation for predicting the peak underwater sound pressure from underwater explosions was developed as a function of range from the source divided by charge weight to the one-third power, $R/W^{1/3}$, herein referred to as scaled range. The origins of scaled range stem from the Kirkwood-Bethe propagation theory[1] and geometric similarity.[2] Peak pressure in the initial positive-going shock wave is given as a function of scaled range by[3]

$$P_{peak} = 52.4 \times 10^6 \left(\frac{R}{W^{1/3}}\right)^{-1.13}, \quad (1)$$

where P_{peak} is the peak pressure in Pa, R is the measurement range in meters, and W is the charge weight in kg TNT. It is important to note that this equation was developed for TNT due to the historical and continued use of TNT as a reference for energy output from high explosives, and assumes a spherical TNT charge of density 1520 kg/m^3. The peak pressure for other forms of explosives can be predicted through use of explosive-dependent coefficients, such as 1.34 for C4 explosives, that are used to scale W to give a TNT-equivalent weight. Also, although originally formulated for spherical charges, the equation has been successfully employed for non-spherical charge geometries.[4–6]

The pressure time signature associated with the initial shock wave can be approximated as decaying exponential with a decay constant θ given by Chapman[4] as

$$\theta = 8.12 \times 10^{-5} W^{1/3} \left(\frac{R}{W^{1/3}}\right)^{0.14}, \quad (2)$$

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where θ is in seconds. Given that the energy flux density, E, for the shock wave is defined as the time integral of the squared pressure divided by the characteristic impedance of the medium, Eq. (1) and Eq. (2) can be combined to yield the empirical relation for an unbounded medium

$$E \propto W^{1/3}\left(\frac{R}{W^{1/3}}\right)^{-2.12}. \tag{3}$$

We remark that proportional relations for energy flux density similar to Eq. (3) are given by Cole,[2] Arons,[3] Slifko,[7] and Wakeley,[8] differing only in the exponent −2.12 by not more than 10%. The differences stem from multiple forms of Eq. (2); here we use Chapman's result given that it originates from a more recent study involving high-resolution instrumentation.

Closely related to energy flux density is the sound exposure level (SEL) that is defined as the time integral of the squared acoustic pressure

$$\mathrm{SEL} = 10\log_{10}\left(\int_0^T p^2(t)dt\right), \tag{4}$$

where SEL is in units of dB referenced to 1 $\mu Pa^2 s$. This is a useful metric to assess cumulative noise exposure as it allows for the comparison of sounds with varying durations[9] and it gives an indication of the total acoustic energy received by an organism.[10] A standard approach to computing SEL is to define the integration period, T, as the time duration that contains 90% of the energy of the received waveform.[11]

In this paper, we present a new set of measurements of peak pressures from explosive sources evaluated as functions of scaled range. Comparing our data with results from previous studies, we show good agreement over 4 orders of magnitude of the scaled range variable, $R/W^{1/3}$. We also evaluate SEL in context of Eq. (3) and present a new empirical equation for this quantity.

2. Measurements

The underwater explosion measurements were conducted on September 11, 2012 during a training exercise for a Navy ordnance disposal team. The measurement site was located 7 km off the coast of Virginia Beach, Virginia in shallow water with a constant depth of 14.7 m and a tidal variation of ±0.3 m over the course of the measurements. Because of recent storm activity the water column was well mixed, and profiles of the sound speed versus depth in the water column put the sound speed at an approximately constant 1528 m/s. Based on archival core samples, the seabed can be described in an approximate sense as sandy sediment with grain size varying between fine and coarse.[12]

Five explosive charges were deployed; tests 1–4 used C-4 charges with a TNT-equivalence of 1.34, while test 5 used a CH-6 charge with a TNT-equivalence of 1.5, giving TNT equivalent weights ranging from 0.1 to 6.0 kg. Detonations occurred at either approximately 9 m depth, or approximately 0.5 m from the bottom. Table 1 provides a summary of the test cases.

Table 1. Test summary.

Test	Local time	Water depth (m)	Explosive	Charge depth	Charge weight (kg)	TNT equivalent	TNT equivalent weight (kg)
1	11:04:09	15.0	C-4	9 m	0.2	1.34	0.3
2	11:12:02	15.0	C-4	∼ 0.5 m from bottom	0.5	1.34	0.6
3	12:49:51	14.8	C-4	9 m	2.3	1.34	3.0
4	13:09:34	14.7	C-4	∼ 0.5 m from bottom	4.5	1.34	6.1
5	16:11:59	14.7	CH-6	9 m	0.07	1.50	0.1

Measurements were made from two small vessels; Vessel 1 located at range 430 m from the source detonation site for tests 1–5 and Vessel 2 located at range 165 m for tests 1–2 and at range 950 m for tests 3–5 (Fig. 1). Acoustic data were recorded from Vessel 1 using a vertical line array (VLA), and an autonomous acoustic recording system. The VLA elements consisted of nine hydrophones (ITC 1032) with receiving voltage sensitivity ranging from −204 to −208 dB re V/μPa depending on the position in the VLA. These were spaced 0.7 m apart with the uppermost hydrophone at depth 6.6 m. Data from the VLA were recorded on a multi-channel coherent data acquisition system (Astro-Med, inc.) for which each channel was recorded at 62 500 samples per second. The autonomous system recorded at depth 12.9 m and consisted of a self-contained data acquisition and storage system (Loggerhead Instruments DSG) and a single hydrophone (HTI-96-min) recording at 50 000 samples per second with a receiving voltage sensitivity of −220 dB re 1 V/μPa. An identical autonomous system was used for Vessel 2 and was deployed at depth 12.2 m (165 m range) and depth 12.7 m (950 m range).

Time series data for test 4 recorded from Vessel 1 on the 12.2 m hydrophone of the VLA and Vessel 2 on the autonomous system are shown in Figs. 2(a) and 2(b), respectively. The first bubble pulse can be seen in each recording arriving ~0.26 s after the primary shock arrival, consistent with empirical predictions.[13] The feature in Fig. 2(a) arriving ~0.12 s after the shock wave (center frequency ~35 Hz) is consistent with an Airy phase region assuming nominal geoacoustic parameters associated with sandy sediments and given water depth, and this observation is subject of on-going study. [Note that in Fig. 2(b) the longer range places this phase in the vicinity of the first bubble pulse arrival.] Scholte interface waves shown in the inset of Fig. 2(a) were recorded during tests 3 and 4 arriving approximately 3 s after the peak arrival. These

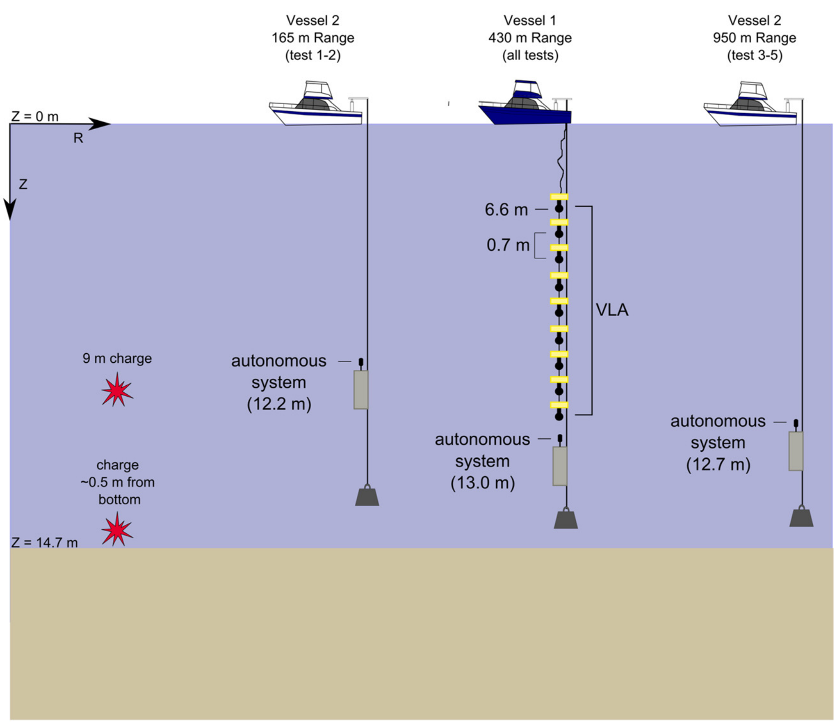

Fig. 1. (Color online) The geometry of the experiment. A nine element vertical line array (VLA) with hydrophones spaced 0.7 m apart and an autonomous system were deployed from Vessel 1. An identical autonomous system was deployed from Vessel 2. Explosive charges were detonated at either 9 m depth or ~0.5 m from the seabed.

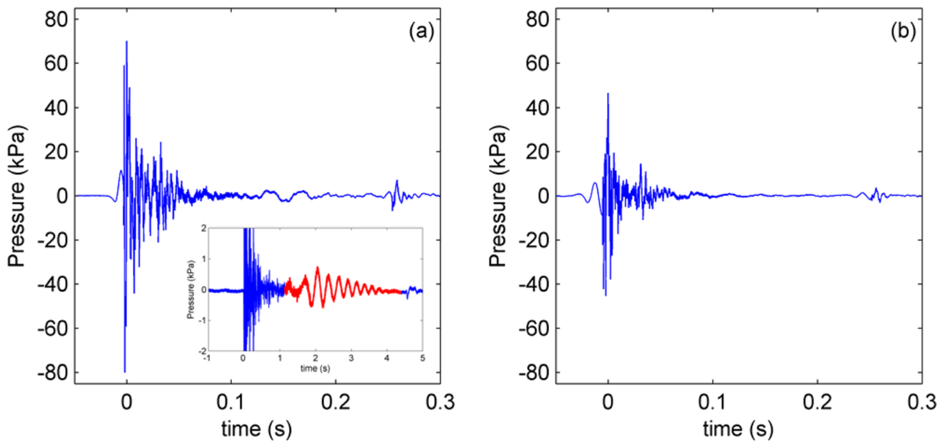

Fig. 2. (Color online) Measured waveform for test 4 from (a) Vessel 1 on the VLA at scaled range 235 m/kg$^{1/3}$, and (b) Vessel 2 on the autonomous system at scaled range 520 m/kg$^{1/3}$. The multipath arrival of the shock is between 0–0.1 s and the bubble pulse is at approximately 0.25 s. The feature arriving ∼0.1 s after the shock wave in (a) is assumed to be related to the Airy phase. A Scholte interface wave was measured on the VLA and is shown in the inset of (a) in red. Note the extended time duration shown in the inset for which a highly magnified vertical scale is required to display the Scholte wave.

Scholte waves are of keen interest and also subject of on-going study by our research group; however, they are not relevant to this particular study as the peak pressure of the Scholte wave is typically over 50 dB lower than that of primary water borne contributions and the contribution of the Scholte wave to the SEL is negligible.

3. Range and charge weight relation for peak pressure

The peak pressures from the Vessel 1 and Vessel 2 measurements, defined observationally as the peak of the absolute value of the measured pressure, and the levels predicted by Eq. (1) are plotted with respect to scaled range in Fig. 3 along with experimental results from historical studies, representing more than four orders of magnitude in scaled range. Peak pressures recorded from Vessel 1 on the VLA and autonomous

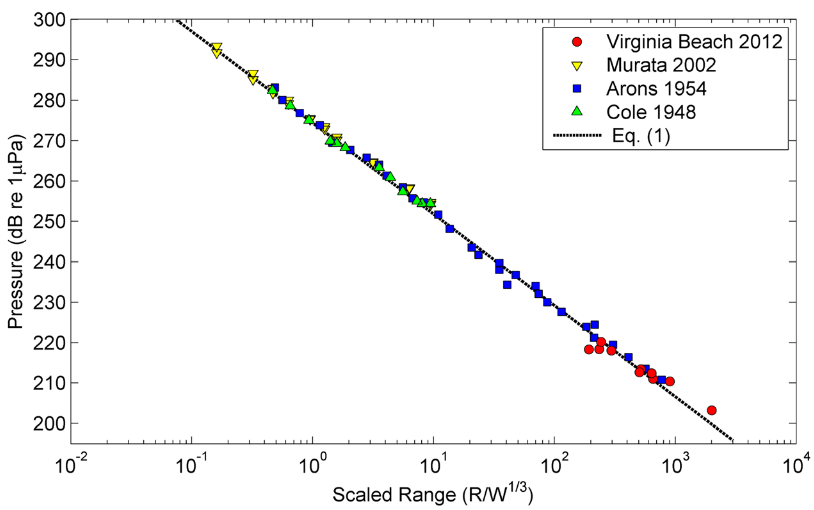

Fig. 3. (Color online) Peak Pressure from Virginia Beach measurements plotted against levels predicted by Eq. (1) and previous measurements of Murata (Ref. 6), Cole (Ref. 2), and Arons (Ref. 3). Historical measurements from Cole and Arons employed TNT charges, while Murata used ammonium nitrate (0.42 TNT equivalence).

system exhibit weak depth dependence (±3 dB), and are therefore presented here as a single averaged value. For the historical data, a root-mean-squared decibel error between the data and Eq. (1) is 1.9 dB, and for the Virginia Beach data this value is 2.4 dB. During the measurements precise source-receiver distances for each test were unavailable and an uncertainty of ±50 m has been assumed. From Eq. (1) this uncertainty translates to ±1 dB at the 430 and 950 m measurement ranges, and increases to ±5 dB at the 165 m measurement range.

4. Range and charge weight relation for Sound Exposure Level

Plotting SEL for tests 1–5 against the energy flux scaling parameter $W^{1/3}(R/W^{1/3})^{-2.12}$ the data collapse well onto a single line given by

$$\mathrm{SEL} = 6.14 \times \log_{10}\left(W^{1/3}\left(\frac{R}{W^{1/3}}\right)^{-2.12}\right) + 219, \tag{5}$$

where SEL is expressed in dB re 1 $\mu\mathrm{Pa}^2\mathrm{s}$ (Fig. 4). Equation (5) results from minimizing the Euclidean 2-norm between the SEL data (expressed in dB) and a two-parameter model using least-squares fitting and gives a root-mean-square decibel error of 1.1 dB (with a resulting r^2 estimate, or coefficient of determination, equal to 0.95). Note that the SEL data reported here include energy contributions from the multi-path propagation of the shock wave and bubble pulses, although the latter, as well as Scholte waves, contribute little to the overall SEL. However, it worth quantifying further the bubble pulse contribution given that the scaling parameter used with Eq. (5) presupposes the shock wave as the dominate contribution to SEL. Specifically, re-evaluating the time series data to include only the shock wave contribution results in at most a 1.5 dB reduction in SEL, suggesting the first bubble pulse contributes at most about 30% of the energy. This result is nominally consistent with that found by computing the SEL of synthetic pressure time series derived from the suite of empirically based equations in Chapman,[4] where the time series can include, or be truncated to exclude, the first bubble pulse.

Finally, the SEL data and Eq. (5) also reflect the influence of the bounded underwater waveguide as distinct from an unbounded medium for which the latter would put the coefficient equal to 10 rather than the value ∼6 that emerges from the

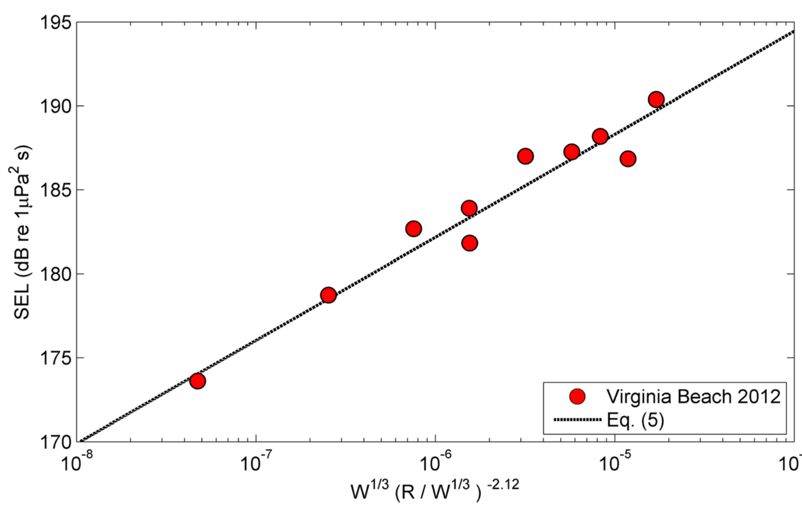

Fig. 4. (Color online) SEL for the Virginia Beach measurements and Eq. (5) plotted against range scaling from Eq. (3).

fitting. This nominally reflects energy conservation in a waveguide where the energy flux will tend to go as 1/R which would put the coefficient exactly equal to 5.

5. Summary and conclusions

In this paper peak pressures and sound exposure levels (SEL) from underwater explosions collected 7 km off the coast of Virginia Beach, Virginia in September 2012 are presented. A semi-empirical equation for peak pressure, Eq. (1), developed in the years after World War II is consistent with these new results. A separate semi-empirical equation for SEL which employs a scaling approach for energy flux density is defined here, Eq. (5). This equation shows promise for the prediction of SEL in shallow water, insofar as it compares well with data measured over the range 170 to 950 m, representing approximately 10 to 70 waveguide depths.

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References and links

[1] J. G. Kirkwood and H. A. Bethe, "Progress report on 'The pressure wave produced by an underwater explosion I,'" National Defense Research Committee, Office of Scientific Research and Development (1942).

[2] R. H. Cole, *Underwater Explosions* (Princeton University Press, Princeton, NJ, 1948), pp. 110–242.

[3] A. B. Arons, "Underwater explosion shock wave parameters at large distances from the charge," J. Acoust. Soc. Am. **26**, 343–346 (1954).

[4] N. R. Chapman, "Measurement of the waveform parameters of shallow explosive charges," J. Acoust. Soc. Am. **78**, 672–681 (1985).

[5] J. B. Gaspin, J. A. Goertner, and I. M. Blatstein, "The determination of acoustic source levels for shallow underwater explosions," J. Acoust. Soc. Am. **66**, 1453–1462 (1979).

[6] K. Murata, K. Takahashi, and Y. Kato, "Precise measurements of underwater explosion performances by pressure gauge using fluoropolymer," J. Mater. Process. Technol. **85**, 39–42 (1999).

[7] J. F. Slifko, "Pressure-pulse characteristics of deep explosions as functions of depth and range," report (United States Naval Ordnance Laboratory, White Oaks, MD, 1967).

[8] J. Wakeley, "Pressure-signature model for an underwater explosive charge," U. S. Navy J. Underwater Acoust. **27**, 445–449 (1977).

[9] B. L. Southall, A. E. Bowles, W. T. Ellison, J. J. Finneran, R. L. Gentry, C. R. Greene, D. Kastak, D. R. Ketten, J. H. Miller, P. E. Nachtigall, W. J. Richardson, J. A. Thomas, and P. L. Tyack, "Marine mammal noise special issue: Exposure criteria: Initial scientific recommendations," Aquat. Mamm. **33**(4), 411–522 (2007).

[10] A. N. Popper and M. C. Hastings, "The effects of anthropogenic sources of sound on fishes," J. Fish Biol. **75**, 455–489 (2009).

[11] P. T. Madsen, M. Johnson, P. J. O. Miller, N. A. Soto, J. Lynch, and P. Tyack, "Quantitative measures of air-gun pulses recorded on sperm whales (*Physeter macrocephalus*) using acoustic tags during controlled exposure experiments," J. Acoust. Soc. Am. **120**, 2366–2379 (2006).

[12] C. S. Hardaway, C. H. Hobbs III, and D. A. Milligan, "Investigations of offshore beach sands: Virginia Beach and Sandbridge, Virginia," report (Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, VA, 1995).

[13] N. R. Chapman, "Source levels of shallow explosive charges," J. Acoust. Soc. Am. **84**, 697–702 (1988).