ACCOUNTING FOR SEA FLOOR PROPERTIES IN THE ASSESSMENT OF UNDERWATER NOISE RADIATED FROM SHIPS IN SHALLOW WATER

V Meyer Naval Group Research, Ollioules, PACA, France
C Audoly Naval Group Research, Ollioules, PACA, France

To minimize the impact of human activities on marine fauna, efforts need to be taken to reduce underwater noise due to shipping by first defining procedures to measure radiated noise from ships. The signal received by a hydrophone array placed in the vicinity of the ship depends on the environment and the measurement configuration. For deep waters, standards have been published to estimate the noise source level taking into account the geometric losses and the effect of the surface. In shallow waters, underwater acoustic propagation is influenced by the interactions with the surface and the sea bottom. Using numerical simulation, an empirical formula has been defined to correct the influence of the environment and estimate the noise source level. However, this empirical formula is only valid for sandy bottoms. The present work aims at correcting the formula to extend its validity to more types of sea bottom. Simulations are carried out using the open source codes: wavenumber integration in the low frequency range and beam-tracing in the high frequency range. The influence of shear waves in the sea floor is going to be investigated. Robustness of the empirical formula will be tested on different water depths and measurement ranges.

INTRODUCTION

Safeguarding marine mammals' habitat has been a rising concern for the last decades. Underwater noise radiated by ships is one of the threats and needs to be controlled to achieve sustainable oceans[1]. Two procedures for assessing the radiated noise level and the noise source level have already met the consensus of the scientific community and have been published in two standards[2,3]. However, these procedures are only applicable in deep waters, where the reflections of the acoustic waves on the sea bottom are negligible. In shallow waters, multiple reflections on the sea surface and the sea bottom complicate the evaluation of the source level.

Preliminary studies published last year proposed an empirical analytical formula to correct the influence of the multiple reflections in shallow waters[4]. This empirical formula is based on numerical simulation of different measurement configurations, where the measurement distance, the water depth and the source depth are varying. It was shown that the formula is valid for a variety of speed of sound profiles and is slightly influenced by the immersion of the hydrophone array[5]. Additional simulations have shown a good match with the analytical formula for a sandy sea floor but large deviations for a rocky sea floor[6]. The objective of this paper is to understand the influence of the sea bottom properties and to attempt taking its influence into account.

METHODOLOGY

Let us consider the reference situation described on Fig. 1. The ship is modeled by an omnidirectional point source, represented by the red dot at a depth of $d_s = 4$ m. It is a very simplistic approach of modeling a ship, as in practice it has several acoustic sources involving surface radiation from the hull. However this assumption was taken to run preliminary simulations to understand the phenomena linked to shallow water propagation. Three hydrophones represented by blue dots are placed at a distance $d_{CPA} = 100$ m from the source, the first one at depth $H_{top} = 15$ m, and the two consecutive hydrophones are separated by the same distance $\Delta H = 20$ m. Water depth is $H = 60$ m. The sea surface is considered to be perfectly flat and the water domain is homogeneous with a speed of sound of $c_0 = 1500$ m/s and a density of $\rho_0 = 1024$ kg.m^{-3}. It has been shown that the sea surface has mainly an influence in the high frequencies and can be treated separately in a later step[7]. The floor is also perfectly flat and is characterized by its density ρ, its longitudinal waves speed c_p and attenuation η_p, and its transversal waves speed c_s and attenuation η_s. Different sea floor properties are tested, according to the Table 1 taken from Ref. 8.

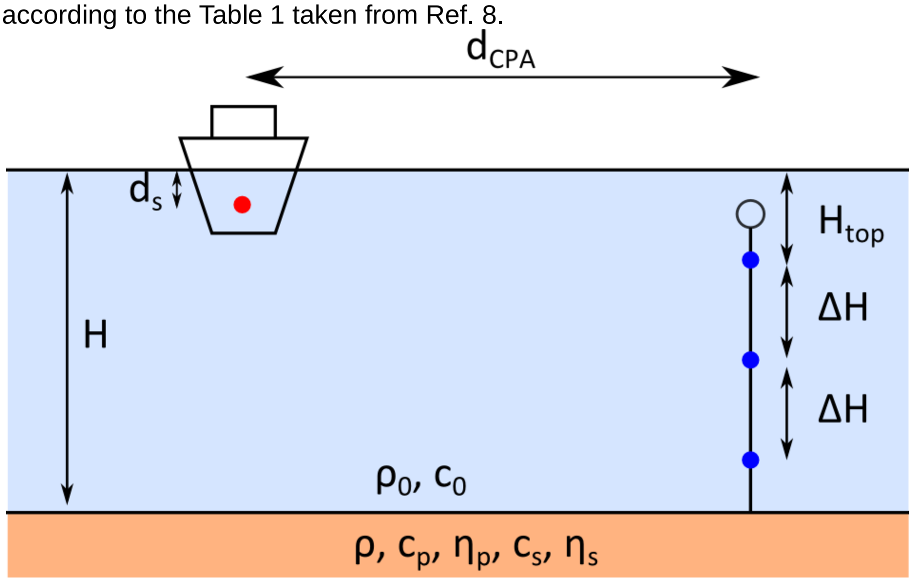


Figure 1. Sketch of the measurement configuration. The sound source is represented by a red dot and the hydrophones by blue dots.

Table 1. Sea floor properties.

Floor type	**ρ (kg.m^{-3})**	**c_p (m/s)**	**η_p (dB/λ)**	**c_s (m/s)**	**η_s (dB/λ)**
Clay	1500	1500	0.2	80	1
Silt	1700	1575	1	80	1.5
Sand	1900	1650	0.8	110	2.5
Gravel	2000	1800	0.6	180	1.5
Moraine	2100	1950	0.4	600	1
Chalk	2200	2400	0.2	1000	0.5
Limestone	2400	3000	0.1	1500	0.2
Basalt	2700	5250	0.1	2500	0.2

The transmission losses (TL) between the source and the hydrophones are simulated using open-source codes from the Acoustics Toolbox[9]. The wavenumber integration code Scooter and the beam-tracing code Bellhop, both developed by M. B. Porter, have been used in the low frequency range (<1000 Hz) and in the high frequency range (>1000 Hz), respectively. These codes have been validated for short range propagation by comparison to experimental data[10]. Calculations were performed on discrete frequencies and averaged on third-octave bands between 10 Hz and 20 kHz, with 11 frequencies per band.

Two quantities are defined to describe the radiated noise from a ship:

- The Radiated Noise Level L_{RN}, which corresponds to the radiated pressure measured in a given environment[2].
- The Source Level L_S, which correspond to the power level of the source and is independent from the environment.

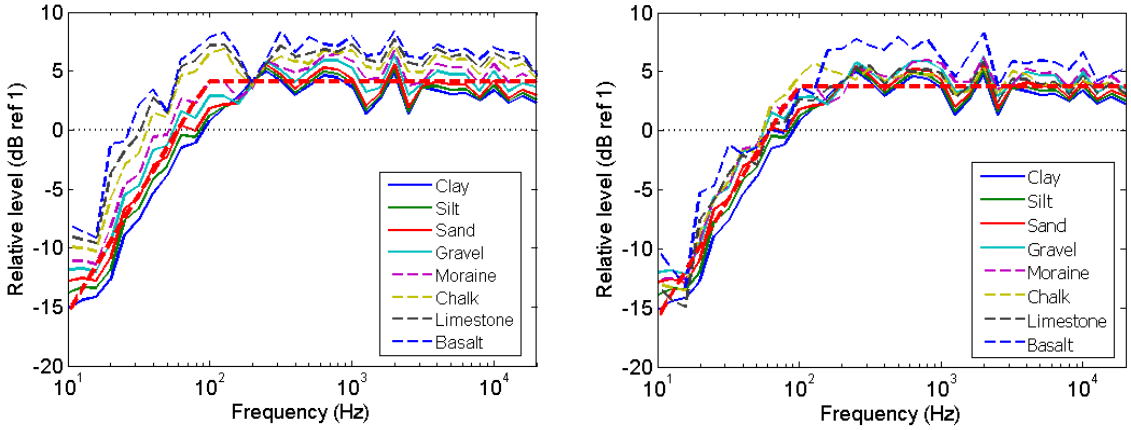
These two quantities are linked through the relative level ΔL:

$$L_S = L_{RN} - \Delta L \quad (1)$$

For each hydrophone, the TL is corrected by a spherical geometric loss of $20\log_{10} R$, with R the distance between the source and the hydrophone. This quantity is quadratically summed over the three hydrophones to yield L_{RN}. In the simulations the source is supposed to be of unitary amplitude, so that $L_S = 0$ dB. In this situation, Eq. 1 shows that $L_{RN} = \Delta L$. This quantity is going to be studied throughout the document.

INFLUENCE OF THE TRANSVERSE WAVES

The variation of the sea floor properties have been investigated previously, but neglecting the transversal waves in the sea floor (domain modeled as a fluid domain)[5]. The results of these simulations are shown on Fig. 2a for the eight types of sea floor presented in Table 1. On Fig. 2b the sea bottom is modeled as a solid, taking into account the transverse waves in the sea floor domain. On both figures, the red doted lines show the empirical model as expressed in Ref. 4. The results of Fig. 2 suggest that the shear waves do not have an influence on the “soft” materials (clay, silt, sand, gravel). On the contrary, the measured level decreases for the “hard” materials (moraine, chalk, limestone, basalt). For the basalt however, the decrease appears mainly at low frequencies (below the inflexion point at 100 Hz). We can see that in this situation, the empirical model fits well at low frequencies, but would need some corrections for the hard materials in the high frequencies. It also needs to be verified if this observation is valid for different H, d_{CPA} and d_s.



(a) (b)

Figure 2: Relative level from a unitary source averaged over the 3 hydrophones for the eight different types of sea floor (a) without shear waves, (b) with shear waves.

EMPIRICAL MODEL

The empirical formula proposed in the previous study[4] was defined by two straight lines (see the thick red dashed line on Figure 2). In the low frequency part, the relative level follows a slope of 20 dB per decade to account for the dipole effect. In the high frequency part, the relative level is constant, because of the multiple reflections of the acoustic waves on the bottom and surface, averaged over third-octave bands. Let us define the cut-off frequency f_0 as the transition frequency between the low and high frequency behaviors. Knowing this trend, the relative level can be formulated as a second-order high-pass filter:

$$\Delta L(f) = 10\log_{10}\left(\frac{K}{\frac{f_0^2}{f^2} + \frac{i}{Q}\frac{f_0}{f} - 1}\right) \qquad (2)$$

where $= 2\max\left(\sqrt{\frac{d_{CPA}}{H}}, 1\right)$, $f_0 = \frac{c_0}{2\pi d_s}\sqrt{K}$, $i^2 = -1$ and $Q = 0.75$. The curve has a smoother transition zone around the cut-off frequency f_0 than for the formula found in Ref. 4.

The factor 2 in the coefficient K represents the fact that the energy is doubled in the high frequency because of the sea surface. When it comes to hard sea floor, it can be expected that this factor is doubled because of additional reflections on the sea floor. We therefore propose to modify the formula as follows:

$$\Delta L(f) = 10\log_{10}\left(\frac{\varepsilon K}{\frac{f_0^2}{f^2} + \frac{i}{Q}\frac{f_0}{f} - 1}\right) \qquad (3)$$

where $\varepsilon = \begin{cases} 1, & \text{if the floor is considered soft} \\ 2, & \text{if the floor is considered hard} \end{cases}$
In practice, the sea floor can be considered to be hard if its acoustic impedance $Z_B = \rho c_p$ is much larger that the acoustic impedance of water, $Z_0 = \rho_0 c_0$. Figure 3 presents the results for the test case presented in the previous section for sea floor made of sand (soft floor) and basalt (hard floor). For the soft floor, the empirical formula fits very well the simulated data. For the hard floor, the simulated data follows an increase of 20 dB per decade in the low frequency range and a plateau at approximately 7 dB after the inflexion point. Bigger differences can be seen between 50 and 125 Hz, where the simulated data is lower (up to 5 dB difference at 80 Hz). Also, in the frequencies higher than 2.5 kHz the simulated level tends to decrease. However, the empirical model gives a good trend of the relative level in both soft and hard floor configurations. To better quantify the quality of the empirical model, let us define the relative quadratic error δ between the model and the simulated data as the average over the whole frequency range of the quadratic difference of the values in dB:

$$\delta = \sqrt{\frac{\sum\left|\Delta L^2_{empirical} - \Delta L^2_{simulated}\right|}{N_f}} \tag{4}$$

Where N_f is the number of third-octave bands central frequencies (namely $N_f = 34$ in our case, for calculations between 10 Hz and 20 kHz). In this case, the average difference for both floor types is lower than 1 dB.

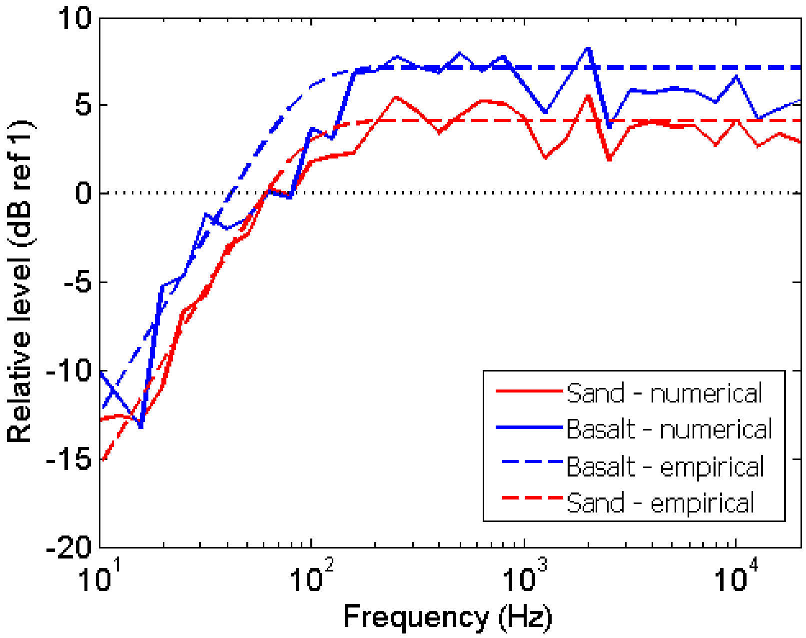


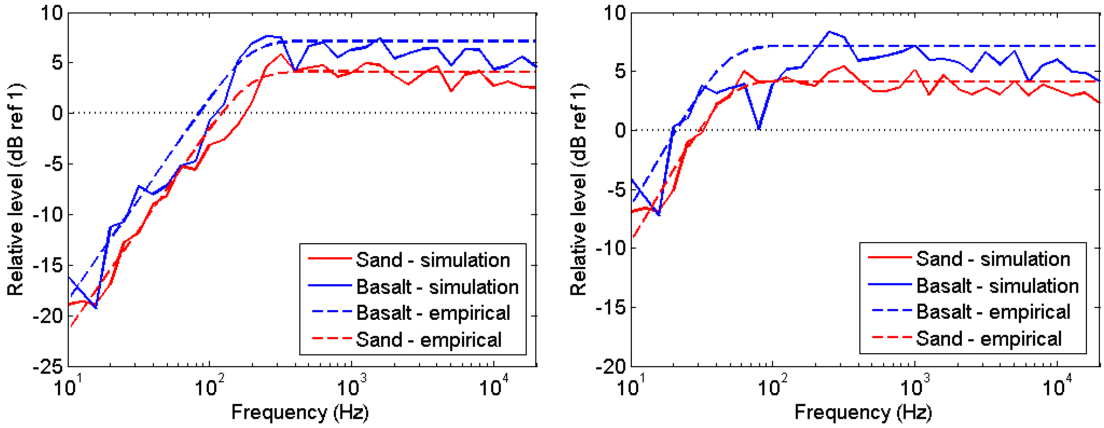
Figure 3: Relative level for the reference test case.

VALIDITY OF THE APPROACH

Influence of the source depth

The empirical formula is compared to simulated data on Fig. 4 for source depths of 2 and 8 m for floors made of sand and basalt. The other parameters remain unchanged ($H = 60$ m and $d_{CPA} = 100$

m). The fit for $d_s = 2$ m is good on the whole frequency range, with relative quadratic error lower than 1 dB. For $d_s = 8$ m the fit is overall good (relative error less than 1 dB), except in the region of the cut-off frequency (around 80 Hz) where there is a 7 dB difference.

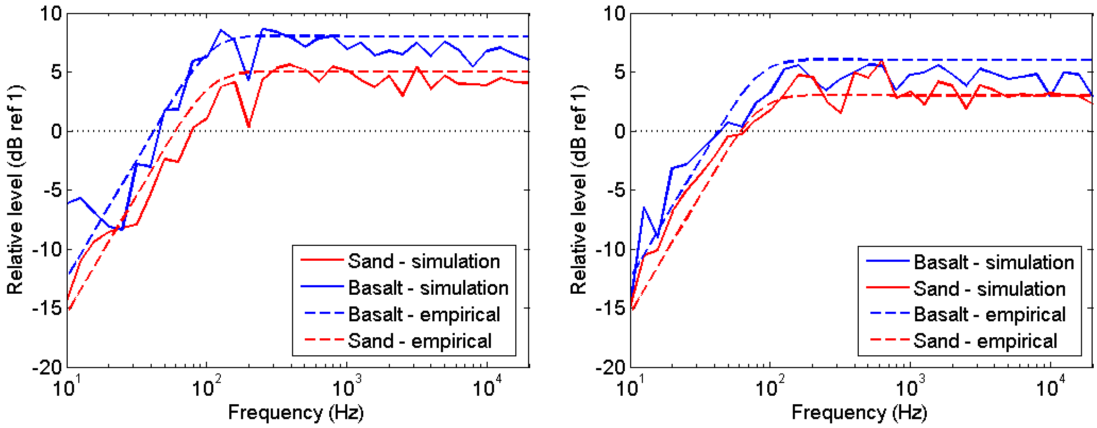


(a) (b)

Figure 4: Relative level for (a) $d_s = 2$ m, (b) $d_s = 8$ m.

Influence of water depth

Coming back to a source depth of $d_s = 4$ m, two other water depths are simulated: $H = 40$ m and $H = 100$ m. In these situations, the hydrophone spacing is modified to $\Delta H = 10$ m in the first case and $\Delta H = 40$ m in the second case. Making these choices, the deeper hydrophone is always at 5 m from the sea bottom. The measurement distance remains at $d_{CPA} = 100$ m. The results are presented on Fig. 5, exhibiting a good fit for the lower water depth ($\delta = 1.2$ dB for the sand, $\delta = 0.8$ dB for the basalt). For $H = 100$ m, it seems that the empirical formula is a bit overestimating the relative level. The sea bottom being further from the source in this case, its effect is weaker. The overall error remains low in both cases ($\delta = 1$ dB for the sand, $\delta = 0.7$ dB for the basalt).



(a) (b)

Figure 5: Relative level for (a) $H = 40$ m, (b) $H = 100$ m.

Influence of measurement distance

Setting again $d_s = 4$ and $H = 60$ m, the influence of the measurement distance is observed with two additional values of d_{CPA}: 200 m and 300 m. The results presented in Fig. 6 suggest that the empirical formula accounts well for the changes in the measurement distance (relative errors lower than 1.5 dB for sand and lower than 1 dB for basalt). However, the simulated relative level tends to decrease in the high frequencies (from 10 kHz for Fig. 6a, from 5 kHz for Fig. 6b). It is not clear at this stage of the study if this decrease comes from a physical phenomenon or is linked to the simulation. This aspect needs to be further investigated.

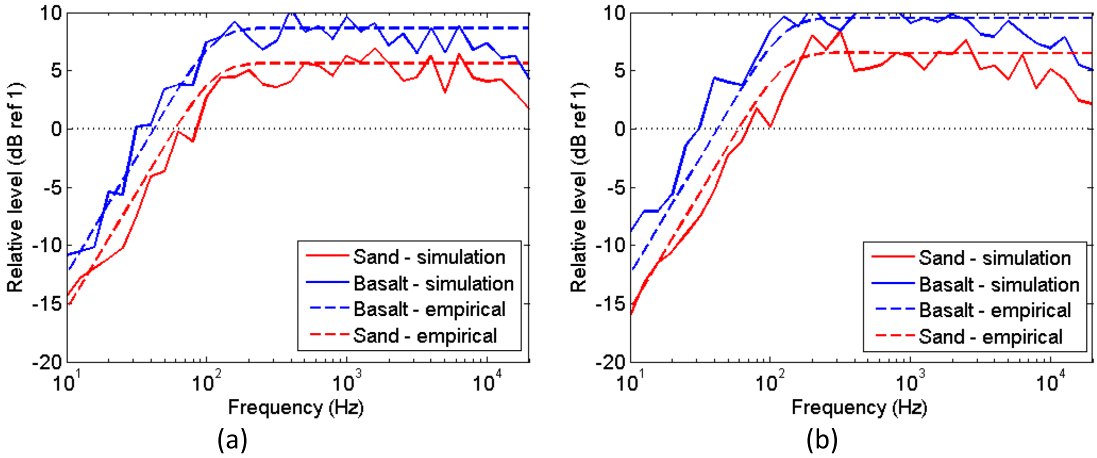


Figure 6: Relative level for (a)* $d_{CPA} = 200$ *m, (b)* $d_{CPA} = 300$ *m.

Additional simulations are run for a source depth of $d_s = 4$ m, a water depth of $H = 100$ m and two measurement distances (200 and 300 m). The relative levels are presented on Fig. 7. The empirical formula shows still a good fit to the simulated data (δ around 1.5 dB for sand and 0.8 dB for basalt).

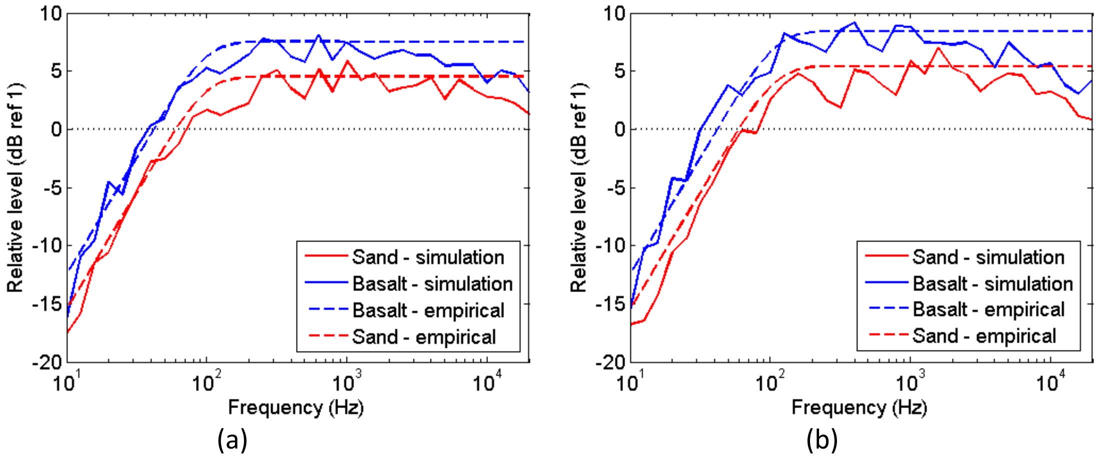


Figure 7: Relative level for $H = 100$ ***m and (a)*** $d_{CPA} = 200$ ***m, (b)*** $d_{CPA} = 300$ ***m.***

CONCLUSION

Open-source simulation codes have been used to simulate the measured level radiated by a source close to the surface for different shallow water configurations, taking into consideration the effect of different sea floors. The simulations use strong assumptions, namely a punctual and omnidirectional source, a perfectly flat sea surface and a flat and homogeneous sea bottom. It has been shown that the sea floor has a big influence on the measured level. An empirical formula has been proposed to estimate the source level from the measurement configuration. The formula shows a good fit with simulated data for sea bottoms made of sand and basalt. Further work consists in checking other types of sea floor, and testing multi-layered environments (for instance, a layer of sand over a rocky bottom). In particular, formulas given in section 4 should evolve to take into account intermediate cases between soft and hard sea floors. Also, the availability of experimental results from measurement campaigns at sea would be helpful to confirm the validity of the approach.

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