Effects of Depth-varying Compressional Wave Attenuation on Sound Propagation on a Sandy Bottom in Shallow Water

천해 사질 퇴적층에서 종파감쇠계수의 깊이별 변화가 음파손실에 미치는 영향

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ABSTRACT

The characteristics of bottom sediment may be able to vary within a few meters of depth in shallow water. Since bottom attenuation coefficient as well as sound velocity in the bottom layer is determined by the composition and characteristics of sediment itself, it is reasonable to assume that the bottom attenuation coefficient is accordingly variable with depth. In this study, we use a parabolic equation scheme to examine the effects of depth-varying compressional wave attenuation on acoustic wave propagation in the low frequency ranging from 100 to 805 Hz. The sea floor under consideration is sandy bottom where the water and the sediment depths are 40 meters and 10 meters, respectively. Depending on the assumption that attenuation coefficient is constant or depth-varying, the propagation loss difference is as large as 10 dB within 15 km. The predicted propagation loss is very much comparable to the measured one when we employ a depth-varying attenuation coefficient.

요 약

천해 해저 퇴적물의 특성은 수 미터 깊이에서도 변할 수 있다. 퇴적층에서의 음속 뿐만 아니라 감쇠계수도 퇴적물의 성분과 특성 자체에 의해서 결정되므로 감쇠계수는 퇴적층 깊이에 따라 가변적이라고 여기는 것이 합리적이다. 본 연구에서는 포물선 방정식 기법을 도입한 음향모델을 이용하여 퇴적층 종파 감쇠계수의 변화가 100-805 Hz 대역 음파의 전파에 미치는 영향을 고찰하였다. 대상 해역은 해저면이 사질로 구성되어 있고, 수심과 퇴적층의 깊이는 각각 40 m, 10 m이다. 감쇠계수가 퇴적층 깊이에 따라 일정하게 또는 가변적으로 가정함에 따라 음파의 전파손실은 15 km 거리에서 10 dB 까지 차이가 발생한다. 모델에 의하여 계산된 전파손실은 감쇠계수를 퇴적층 깊이에 따라 변하게 할 경우 실측된 전파손실과 잘 일치한다.

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I. Introduction

When an acoustic wave travels in shallow water, it is mainly controlled by the acoustic properties of the bottom. The dominant loss mechanisms associated with the bottom have been reported as compressional wave attenuation, scattering loss, and conversion of incident compressional wave to shear waves.[1-3] In this paper, we consider only the effects of compressional wave attenuation on acoustic wave propagation.

Since there are relatively few measurements of attenuation in real sediments at the low frequency, attenuation is usually estimated from geoacoustic models. Among these, many researchers adopted Hamilton's geoacoustic model to calculate propagation loss. Hamilton[4-6] complied field measurement data and suggested empirical formulas for the estimation of sound velocity and the attenuation related to mean grain size or porosity in sediment. He also showed that the attenuation coefficient of bottom sediment is nearly proportional to the first power of frequency.

In process matching the predicted propagation loss to the measured one in the low frequency, Ferla et al.[7] found that they agree very well if the model includes shear wave attenuation in addition to compressional one. However, the shear wave required in the model is around 600 m/sec and appears to be greater than any other measured one in the natural sediments to date. Hence, he suggested that there exist an additional bottom attenuation mechanism not included in the preceding theory of elastic media where compressional wave attenuation varies linearly with frequency.

On the other hand, from the analysis of field and laboratory data, Stoll[8,9] reported that the linear frequency dependence of attenuation coefficient is unacceptable in nearly all cases of marine sediments. Some authors[10-13] attempted to reveal the frequency dependence of attenuation coefficient by a normal mode scheme. By adjusting input parameters and making the calculated results coincide with the measured data, they deduced attenuation coefficients in a sediment which have nonlinear frequency dependence. This interpretation is based on the assumption that attenuation coefficient at any frequency is constant with a bottom sediment depth. In shallow water, however, there may exist significant changes of material properties over a few meters of depth even in sands of homogeneous composition.[5,14] In addition, variations of material properties with depth can result in variations of bottom attenuation. There is little reason to assume that bottom attenuation at any frequency is constant with depth.

In this study, we use a parabolic equation scheme to verify the effects of depth-varying compressional wave attenuation on acoustic wave propagation in shallow water in the low frequency ranging from 100 to 805 Hz. The sea floor under consideration is sandy bottom where the depths of water and sediment are 40 meters and 10 meters, respectively. We also compare the measured propagation loss with the predicted one under the assumption that bottom attenuation exponentially decreases with depth and linearly increases with frequency.

II. Effects of bottom attenuation on wave propagation

A. Input parameters

Input paramters of the model are shown in Fig. 1. The water depth is about 40 meters. The sea floor is flat sandy bottom whose depth is about 10 meters. We consider three different cases of bottom attenuation with depth : Case I) exponential decrease from 0.8 dB/λ to 0.44 dB/λ where λ is wavelength, Case II) constant value of 0.8 dB/λ, and Case III) constant value of 0.4 dB/λ. The attenuation coefficients are the values with respect to the source frequency of 100 Hz. The exponential decrease of attenuation with depth has been reported by Hamilton[5] in sandy bottom. Except for the bottom attenuation, all other input parameters remained the same for the three cases. In particular, sound speeds in a sediment are assumed to increase exponentially with depth. This is known as common in sandy bottom.[?] In calculating propagation loss, a numerical model based on PE scheme is used.

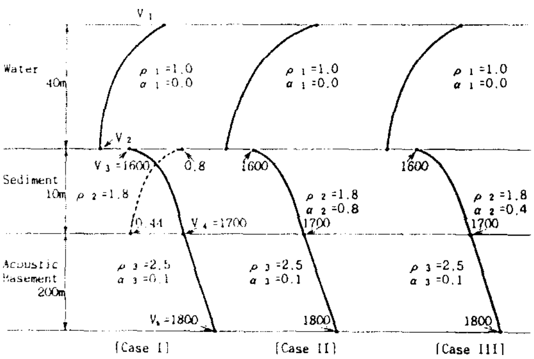

Fig.1. Input parameters for the calculation of propagation loss for the three different cases. Case Ⅰ : bottom attenuation decreases exponentially from 0.8 dB/λ to 0.44 dB/λ with sediment depth, Case Ⅱ, Ⅲ : bottom attenuations are constant(0.8 dB/λ and 0.4 dB/λ) over sediment depth. V : sound velocity(m/sec), α : attenuation coefficient(dB/λ), ρ : density(g/cm³)

Fig.2 shows the water temperature profile used in calculating propagation loss. The profile was obtained in a site near the receiver during the propagation loss measurement. From the temperature profile, it can be shown that the temperatures are increasing or nearly constant from surface to 9 meter depth. Meanwhile, the strong thermocline, whose gradient is about 0.7℃/m, is formed from 10 to 20 meter depth.

B. Predicted propagation loss

Fig.3 shows the model outputs for the three different cases of input parameters in Fig.1. The sound profile, which is obtained using the temperature profile in Fig.2, is used for the three cases of calculations. Relative propagation loss is

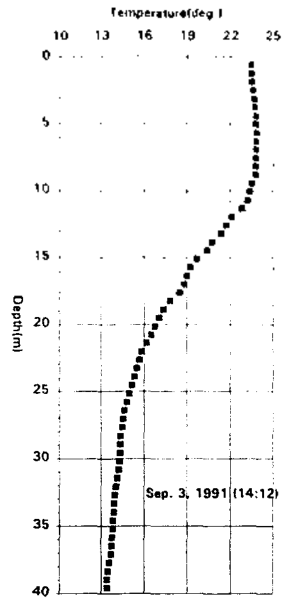

Fig.2. Water temperature profile obtained during the propagation loss measurement on September 3, 1991.

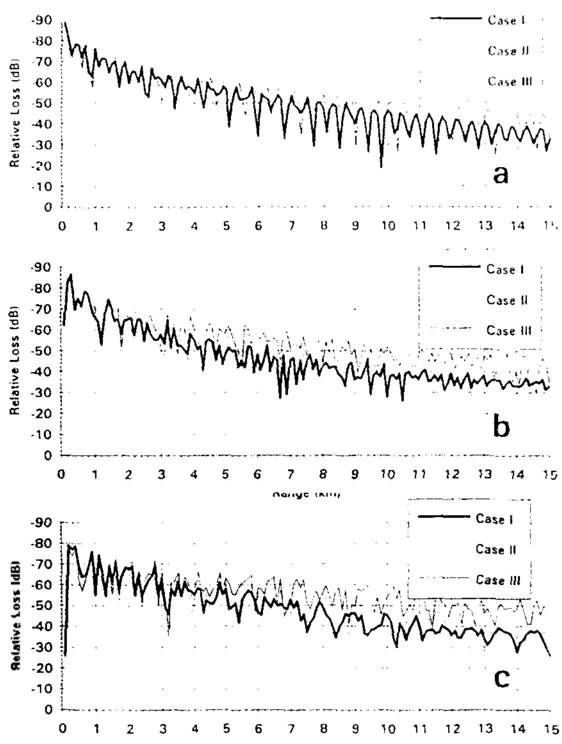

Fig.3. Calculated propagation loss for the three cases in Fig.1. (a) 130 Hz, (b) 505 Hz, (c) 805 Hz.

plotted in every 100 meters. The source and the receiver depths are 10 meters and 40 meters, respectively.

At the source frequency of 130 Hz, the loss in Case Ⅰ is roughly 3 dB greater than that in Case Ⅲ, and about 4 dB less than that in Case Ⅱ within 15 km. When the source frequency is 505 Hz, there are some remarkable changes in the loss trend. That is, the loss difference increases as much as 10 dB between the Case Ⅰ and Ⅲ while decreases to 3 dB between the Case Ⅰ and Ⅱ. This is because the loss increasing rate with range in Case Ⅱ and Ⅲ is less than that in Case Ⅰ. This trend is more obvious in the case of 805 Hz. Moreover, the loss in Case Ⅲ is less than that in Case Ⅰ over 5 km range. Namely, when the bottom attenuation is constant with depth and linear with frequency, the loss increasing rate with range becomes smaller with increasing frequency.

Fig.4 shows the calculated propagation loss, when the source is located at 10 meter depth, for the Case Ⅰ. The relative scale for the propagation loss is shown at the bottom. The attenuation of acoustic energy for 165 Hz is very noticeable in the sediment layer as shown in Fig.4a. That is, the depth into which acoustic energy can penetrate is nearly 50 meters. In the case of 505 Hz, however, the acoustic energy seems to be diffused into the sediment layer, and the penetrating depth is limited to the first few meters of a sediment layer. This also implies that the extents attenuated in a bottom layer depend on frequency. Accoring to a numerical experiment with normal mode scheme,[5] the attenuation is important down to 20 to 30 meters at 50 Hz, but, the first 4-8 meters at 100Hz.

C. Predicted propagation loss with measured one

An experiment has been conducted to measure propagation loss in the shallow water which has

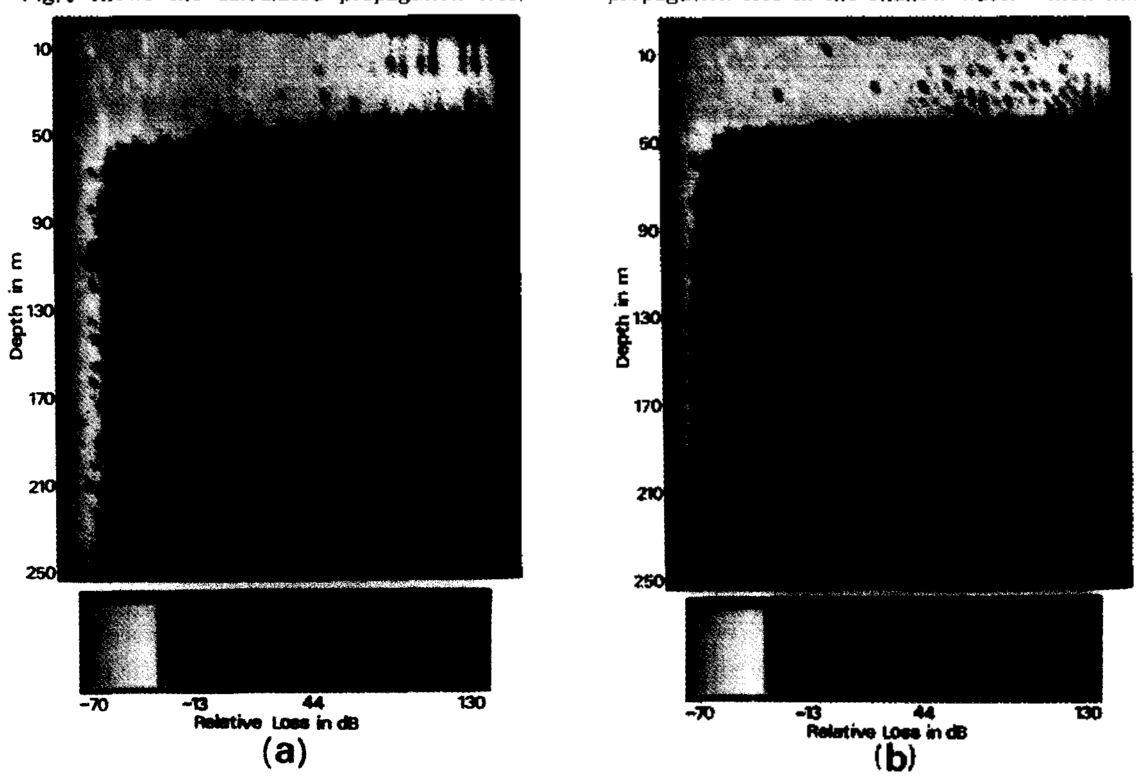

Fig.4. Calculated propagation loss in depth and range for the Case Ⅰ. The horizontal range is 15 km. (a) 165 Hz, (b) 505 Hz.

nearly flat bottom(Fig.5). The bottom thickness is about 10 meters and the sediment type is sand. Source and receiver depths are fixed to 10 meters and 40 meters, respectively. The source frequency is selectable among 100, 130, 165, 505, and 805 Hz and the source level in each frequency is fixed to the value in the range 140-170 dB. While the receiver is fixed, the source is towed toward the receiver over about 14 km range. The exact range between the source and the receiver is obtained using the GPS(global positioning system) of which accuracy is about 5 meters.

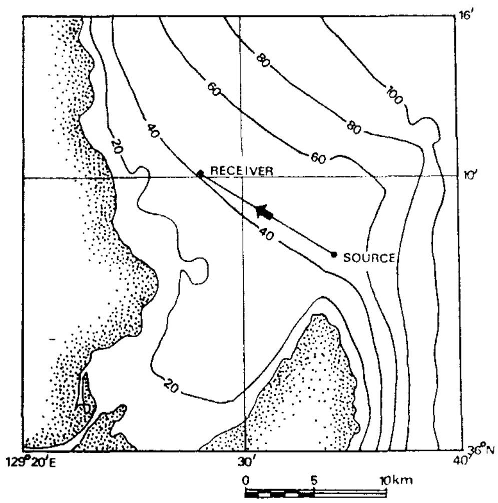

Fig.5. Track line of the sound source towing in the propagation loss measurement on September 3, 1991.

Fig.6 shows comparisons of the predicted propagation loss with the measured one at the frequency of 130, 505, and 805 Hz. The predicted propagation loss is obtained assuming that sediment attenuations vary with depth as the Case I shown in Fig.1. At 130 Hz, the predicted loss is a little bit lower than the measured one within 3 km but agrees very well thereafter. At 805 Hz, the predicted loss is very comparable to the measured one except within 6 km where the difference reaches 5 dB. That is, if we adopt a sediment attenuation so that it varies exponentially with depth, the predicted loss is comparable to the measured one even if an attenuation is still linear with frequency.

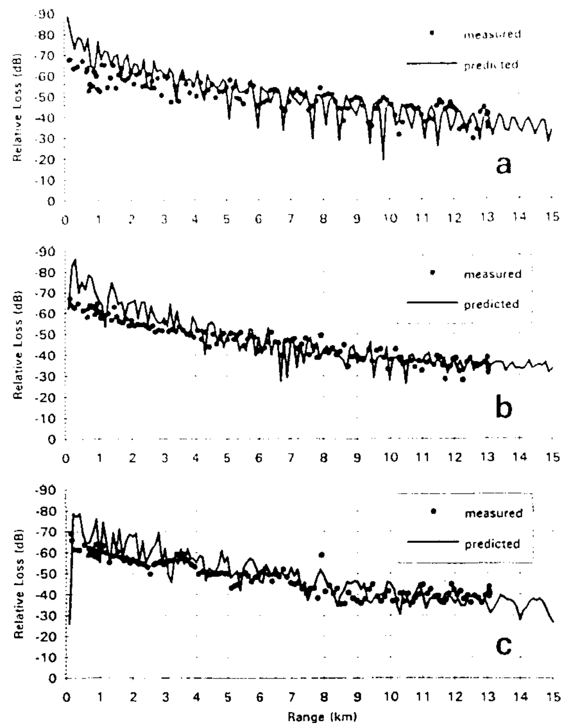

Fig.6. Comparison of the measured propagation loss with the predicted one for the Case I in Fig.1. (a)130 Hz, (b)505 Hz, (c)805 Hz.

III. Discussion

If the loss trends in Case II and III are comparable to that in Case I, the attenuation should be increased nonlinearly with frequency. This fact corresponds to the results of Zhou and Zhang.[13] Zhou and Zhang found that excellant agreement is achieved between the predicted propagation loss and the measured one when the attenuation is proportional to frequency to about the 1.8 power.

The effects of a depth-varying attenuation on wave propagation can be inferred by examining the mode attenuation coefficient in a normal mode. The mode attenuation coefficient δ_n is defined as the imaginary part of the nth eigenvalue k_n of homogeneous wave equation.

$$k_n = \kappa_n + i\delta_n \quad (1)$$

A perturbation solution for δ_n can be developed in terms of the unperturbated Ψ_n and κ_n, where Ψ_n is the nth depth component solution or mode function of wave equation.[16] The δ_n is valid on a condition that attenuation is small over ranges comparable to an acoustic wavelength. And we also assume that the attenuation is so small that the mode function Ψ_n may be used. Under these conditions, δ_n is expressed as

$$\delta_n = \frac{\omega}{\kappa_n} \sum_{m=1}^{M} \rho_m \int_{z_{m-1}}^{z_m} \frac{\alpha(z)}{c(z)} |\Psi_n(z)|^2 dz / A_n, \quad (2)$$

$$A_n = \sum_{m=1}^{M} \rho_m \int_{z_{m-1}}^{z_m} |\Psi_n(z)|^2 dz.$$

Here, A_n is the normalization factor for the nth mode. The density of the mth layer, ρ_m, is assumed to be constant with depth.

If we consider three-layered media(water, sediment, and substrate) whose attenuation is constant in each layer, Eq.(2) can be simplified to

$$\delta_n = \alpha_{sed}\, \gamma_{n1} + \alpha_{bas}\, \gamma_{n2}, \quad (3)$$

$$\gamma_{n1} = \frac{\omega \rho_{sed}}{\kappa_n} \int_{sed} |\Psi_n(z)|^2 / c(z)\ dz / A_n,$$

$$\gamma_{n2} = \frac{\omega \rho_{bas}}{\kappa_n} \int_{bas} |\Psi_n(z)|^2 / c(z)\ dz / A_n.$$

Here, α_{sed} and α_{bas} are the attenuation coefficients of sediment and substrate, respectively. Eq.(3) is simpler than Eq.(2) for the numerical calculations of δ_n but allows unrealistic variations of the attenuation with depth i.e., constant attenuation in each layer. If the attenuation varies with depth, even though the attenuation locally varies linearly with frequency, δ_n computed from Eq.(2) will not be linear with frequency. For the two compressional wave attenuation profiles which vary with depth, Mitchell and Focke[15] obtained two attenuation coefficients from Eq.(2) which are nonlinearly dependent on frequency. Although fully adequate evidence is still unavailable, the transition between frequency-independent and frequency dependent behavior can occur in the very low frequency(< 100 Hz).[17]

IV. Conclusion

Depending on the assumption that a compressional attenuation is depth-varying or constant, the model prediction shows that the difference of propagation loss is as large as 10 dB within 15 km in a sandy bottom. The predicted loss is comparable to the measured one within 5 dB when we employ a depth-varying bottom attenuation. It is suggested that a depth-varying attenuation, which is still remained to be linear with frequency, be a possible mechanism on acoustic wave propagation in shallow water.

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