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Interaction of Mid-to-High Frequency Acoustic Waves with a Sandy Riverbed – Estimation of Geoacoustic Parameters and Modelling of Transmission Loss

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ABSTRACT

Sediment samples collected from 3 shallow water test sites in Idukki reservoir in Kerala are used to estimate the geophysical properties such as porosity, wet bulk density, mean grain size and sediment grain size distribution. The measured geophysical properties are utilised to estimate the geoacoustic parameters, including the compressional speed and compressional attenuation based on effective fluid density model (Biot-Stoll theory), grain and viscous grain shearing model (Buckingham's theory). The derived geoacoustic parameters are then used for modelling the transmission loss in the sediment layer. TL variation is analysed as a function of source depth in the mid-to-high frequency (5-15 kHz) band. Modelling results supports that the penetration is minimal for low grazing angles and higher penetration occurs only at grazing angles greater than the critical angle.

Keywords: Compressional speed; Attenuation; Reflection; Sandy riverbed; Transmission loss

NOMENCLATURE

H : Compressibility
ρ_{eff} : Complex effective density
K_{eff} : Effective bulk modulus
C_o : Wood's sound speed
J : Cylindrical Bessel function

1. INTRODUCTION

Modelling of acoustic wave penetration into seabed sediments can be used as an interpretive tool to investigate the loss mechanisms associated with acoustic propagation[15]. It is essential to understand the seafloor properties and its features for the solution of problems in underwater acoustics where acoustic-seafloor interactions dominate[1]. Hence investigations of physical components like textural and bulk properties of granulated sediment types like sand, silt and clay is necessary which can directly be employed as input parameters in the acoustic theories and model[15,11].

In the present analysis sediment samples obtained from 3 different sites in the Idukki reservoir region in Kerala are used to determine the geophysical and geoacoustic properties. The geophysical properties of sediment samples are estimated in the laboratory immediately after the extraction. These properties are used to estimate parameters such as the compressional velocity and compressional attenuation using established empirical equations from the effective density fluid model, grain shearing model and viscous grain shearing model[21,13,2]

Acoustic wave penetration and propagation within the surficial sedimentary layer are discussed based on modelled transmission loss (TL) as a function of range and depth for different omnidirectional source receiver configurations. The significant bottom loss of the acoustic signals is mainly explained by the mechanism like seafloor reflection, conversion of compressional waves to shear waves, volume absorption and scattering within the sedimentary layers of the bottom[19].

In this paper, transmission loss (TL) modelling is achieved using the acoustic toolbox module – SCOOTER, which is a finite element code developed for computing acoustic fields in range-independent environments. In underwater acoustics, wavenumber integration approaches are often called FFPs (Fast Field Programs) because of the use of Fast Fourier Transforms (FFTs) for evaluation of the spectral integrals[9,20,16].

2. WAVE PROPERTIES OF THE SEDIMENTS

The acoustic behaviour of uppermost sediment layer is broadly classed under fluid and solid theory.

The internal feature of sediment bed is complex with distinguishing characteristics of two-phase systems. It is isotropic in nature. In this porous medium the solids are packed in which void spaces are trapped with water or gas molecules. These void spaces are open and interconnected to each other that there is a continuous motion of pore fluids within the inner void spaces[7]. This dynamical approach of seabed makes it uniquely different from the homogeneous uniform solid or fluid structures. This incorporation of both fluid and solid approximations in modeling significantly rendered to alter the classical theory.

Attenuation mechanism of acoustic signal in poro-elastic medium was first explained by Biot (1956). Acoustic wave propagation in sediment layer accounts for the interaction of

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both the fluid and the solid particles. Later on Stoll (1989) improvised to combined Biot-Stoll theory which stated that dissipation is primarily due to the viscosity of the pore liquids. The number of independent material parameter for Biot-Stoll model is 13 which are cumbersome to implement and characterize. To mitigate these difficulties Williams (2001)[21] proposed effective density fluid model (EDFM) which provides a simpler alternative to the Biot theory and requires a total of 8 input parameters. The Biot-Stoll theory was further advanced to incorporate the physical phenomenon of grain shearing at the contact points which led to the Buckingham theory. Buckingham theory completely neglects the possibility of presence of pore fluid or viscous fluid.

2.1 Biot Theory

The Biot theory is also known as poroelastic theory. This theory treats both porosity and elasticity. Biot intensively studied the sediment characteristics to understand the interaction between the fluid and the solid particles. Surficial layer sediments are porous in which the granular and fluid phases will vibrate differently in response to acoustic excitation and this is highly noticeable in sand[15]. Stoll applied Biot's equation to the sediments like gravel and sand. For further advancement of Biot-Stoll theory, seafloor heterogeneity must also be considered[7]. The attenuation in the sediments varies as f^2 at low frequencies and $f^{1/2}$ at high frequencies which contradicts some of the measurements in sandy sediments. The Biot-Stoll model plays a significant role in the modeling of low frequency sound speed and acoustic attenuation. Biot theory predicts that attenuation scales with viscosity. Stoll uses potentials in terms of the displacement vectors of the skeletal frame (**u**) and water (**U**)

$$u=\nabla\phi+\nabla\times\psi_s \tag{1}$$

$$\beta(u-U) =\nabla\phi_f+\nabla\times\psi_f \tag{2}$$

where, β is porosity, ϕ_s = scalar potential of slow wave and is the ϕ_f = scalar potential of fast wave, ψ_s= vector potential of fast wave and ψ_s = vector potential of slow wave.

Biot's equations for the scalar potentials are then given using a plane wave solution exp[i(kx - ωt)] (Chotiros, 1995)

$$\left(-k^2H\right)\phi_s+k^2C\phi_f=\left(-\omega^2\right)\rho\phi_s+\rho_f\omega^2\phi_f \tag{3}$$

$$(-k^2C)\phi_s+k^2M\phi_f=(-\omega^2)\rho_f\,\phi_s+\frac{\omega^2\alpha\rho_f}{\beta}\phi_f+\frac{i\omega F\eta}{k}\phi_f \tag{4}$$

where, k = permeability, ω= angular frequency, C = elastic coupling coefficient, α = attenuation coefficient and M is the Biot elastic parameter.

2.2 Effective Density Fluid Model (EDFM)

The Biot theory was simplified and contributed to the comprehensive portrayal of effective density fluid model[21]. Effective density of the fluid medium is a complex quantity that differs with physical and measurable density. This model predicts one dimensional compressional wave in the sediment and is compatible with the Rayleigh reflection loss at the water-sediment interface, particularly at the normal interface because the effective density compensate for the Biot slow wave theory. It is shown that, for sand sediments, the dispersion, transmission, reflection, and scattering predicted with the EDFM are very close to the predictions of the Biot theory[16]. The agreement between the EDFM and the Biot theory demonstrates that the bulk modulus and shear modulus of the frame plays a minor role in the reflection, scattering, transmission and in-water backscattering[15]. It states that the compressibility (inverse of modulus) is a linear function of the concentration of the particles in a suspension. The sound speed c_p and attenuation α_p (dB/m) are obtained as:

$$c_p=\sqrt{H/\rho_{eff}} \tag{5}$$

where, H is the compressibility or inverse of the modulus and ρ_{eff} is the complex effective density.

$$\alpha_p=8.686\omega.\mathrm{Im}\sqrt{\rho_{eff}/K_{eff}} \tag{6}$$

where, ω is the angular frequency and the Im […] denotes the imaginary part of a complex value.

2.3 Grain Shearing Model (GS)

The consolidated pack of water bounded granular material acts as a medium for the passage of the slow and fast moving waves. The presence of the compressible viscous fluid within the pores makes the mobility of the grains easier. Such dynamical behaviour of the sediment gives rise to grain-to-grain interactions at the microscopic level[15]. According to Buckingham, G-S dispersion relation for the compressional speed c_p, is given by the expressions:

$$c_p=\frac{c_o}{Re\left[1+\frac{\rho_p+\left(4/3\right)\gamma_s}{c_o^2\rho_o}(j\omega T)^n\right]^{-1/2}} \tag{7}$$

where, $c_o=\sqrt{\frac{K_o}{\rho_o}}$, Wood's Eqn.

And K_o is the bulk moduli of the pore water.

$$X=\frac{\gamma_p+(4/3)\gamma_s}{c_o^2\rho_0} \tag{8}$$

where, X represents dimensionless G-S coefficient and γ_s and γ_p are the shear and the compressional coefficient.

The attenuation α_p (dB/m) is given by:

$$\alpha_p=-\frac{\omega}{c_o}\mathrm{Im}\left[1+\frac{\gamma_p+(4/3)\gamma_s}{c_o^2\rho_0}(j\omega T)^n\right]^{-1/2} \tag{9}$$

where, n is the strain hardening index.

2.4 Viscous Grain Shearing Model (VGS)

The grain-shearing model (G-S) of compressional wave propagation in a saturated granular material, such as marine sediment, is further extended to include the effects of the viscosity of the thin layer of the pore fluid separating known as the Viscous Grain Shearing model (VGS). At higher frequencies, VGS dispersion curves matches with the G-S theory asymptotically.

The following expressions for the sound speed and attenuation:

$$c_p=\frac{c_o}{\mathrm{Re}\left[1+g(\omega)\frac{\gamma_p+(4/3)\gamma_s}{c_0^2\rho_0}(j\omega T)^n\right]^{-1/2}} \tag{10}$$

$$g(\omega) = \left(1 + \frac{1}{j\omega T}\right)^{-1+n},$$

where, g(ω) is the effect of viscous dissipation.

The compressional attenuation is obtained by the expression:

$$\alpha_p = -\frac{\omega}{c_o}\mathrm{Im}\left[1 + \frac{\gamma_p + (4/3)\gamma_s}{c_o^p \rho_0}(j\omega T)^n\right]^{-1/2} \qquad (11)$$

3. SEDIMENT DATA AND MODELLING OF TRANSMISSION LOSS

The sediment texture is determined by the gradistat (Blott, 2020) software meant for the grain size distribution analysis. The statistics of the sediment data is obtained from the laser granulometer analysis or sieve. The mean grain size of the sediment sample is determined by graphically determined value given by Folk and Ward (1957)[10]. The phi scale (Krumbein, 1934)[18] is a logarithmic transformation of the Wentworth (1922)[22] grade scale based on the negative logarithm to the base 2 of the particle size.

$$\phi = -\log_2 2 \qquad (12)$$

where, the diameter of the particle is in mm.

The mean grain size of the sediment sample is determined by the most relevant graphically determined value given by Folk and Ward (1957):

$$M_z = \frac{\Phi_{16} + \Phi_{50} + \Phi_{84}}{3} \qquad (13)$$

where, 16, 50 and 84 percentage of the sample by weight and mean is also measured in phi units and is the most widely compared parameter.

Transmission loss is modelled using the numerical implementation of SCOOTER module which is a finite element code developed for computing acoustic fields in range-independent environments. The method is based on direct computation of the spectral integral (reflectivity or FFP method). Pressure is approximated by piecewise-linear elements as are the material properties. The FIELDS program is used to produce the shade files (TL mosaic). The output is a Green's function file. SCOOTER includes the effect of density gradients within media but does not account for interfacial scattering. The seafloor is assumed to be smooth and hence interface roughness scattering effects are not considered. The sediment volume scattering contributions are also negligible in the absence of any volume in homogeneities.

3.1 Sediment Grain Size Analysis: Results and Discussions

In this section, the weight distribution patterns of the sediments are shown in the form of histograms. The extracted sediment samples from 3 sites are sieved and the percentage weight of the sediments retained on each sieve which is uniformly placed is utilized to determine the sediment weight distribution. The site #1 sample is found to be sandy very fine gravel type. Type #2 is found to be very fine gravelly medium sand and for site #3 it is fine gravelly medium texture based on the mean grain size chart. It is observed that sediment composition of site # 2 and site # 3 are almost similar in texture.

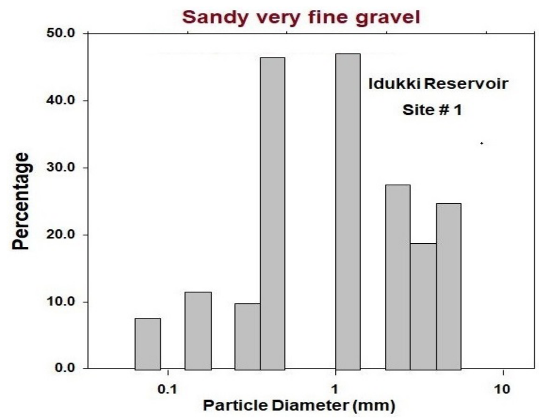

Figure 1. Sediment weight distribution in the sample obtained from site #1 in Idukki Reservoir. The sediment is classified as sandy very fine gravel based on the mean grain size.

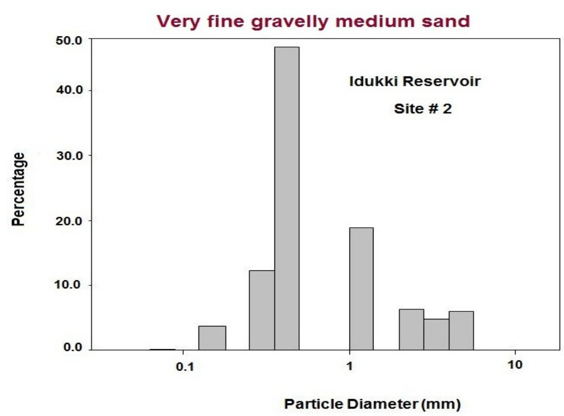

Figure 2. Sediment weight distribution in the sample obtained from site #2 in Idukki Reservoir. The sediment is classified as very fine gravelly medium sand based on the mean grain size.

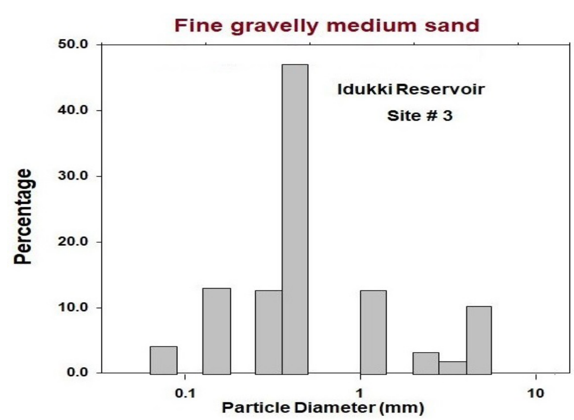

Figure 3. Sediment weight distribution in the sample obtained from site #3 in Idukki Reservoir. The sediment is classified as fine gravelly medium sand based on the mean grain size.

The mean grain size and geophysical parameters obtained from 3 sites in the Idukki reservoir are given in Table 1 and Table 2 respectively. The average grain size in site #1 is found to be -1.833 which is coarser compared to the other 2 sites.

Table 1. Mean grain size calculation for samples obtained site #1-3

Site no.	ϕ_{16}	ϕ_{50}	ϕ_{84}	Mz (Mean grain size) (ϕ)
1	-1.8	- 0.19	1.44	- 0.1833
2	-1.06	1.19	1.45	0.5267
3	- 0.39	1.25	2.51	1.1233

Table 2. Measured geophysical parameters from site # 1-3

Site no.	Porosity (%)	Wet bulk density (g/cm^3)
1	0.13	2.35
2	0.44	1.71
3	0.35	2.06

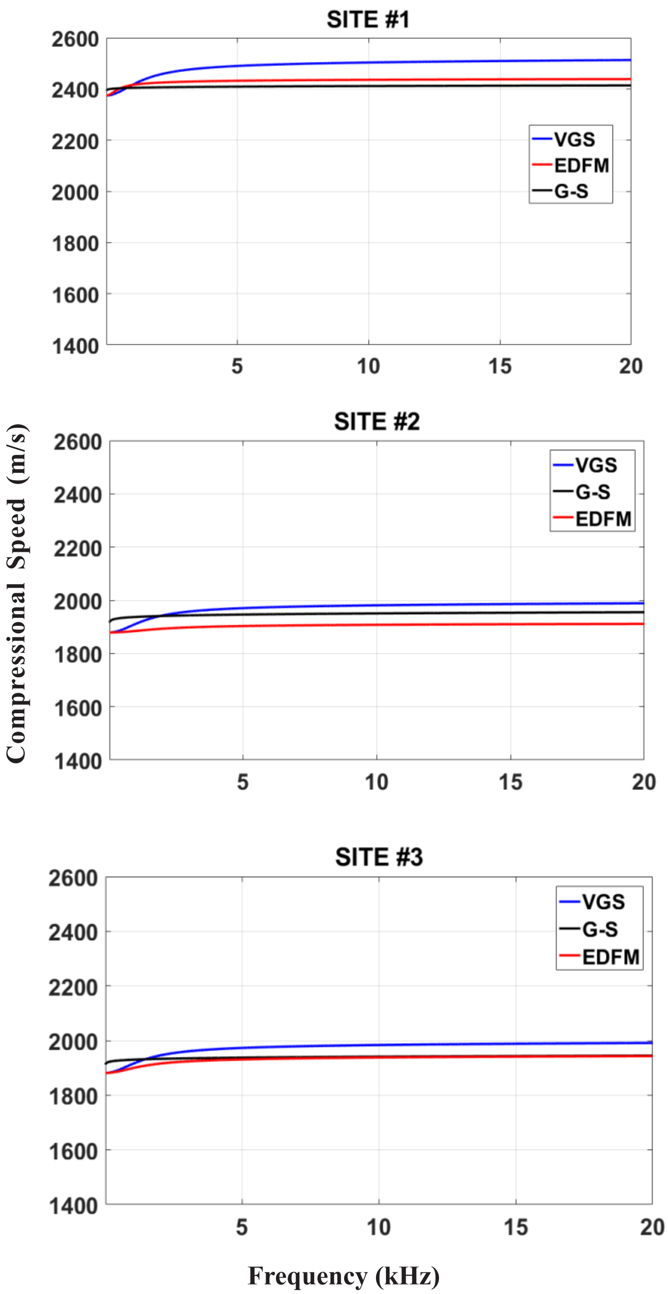

Figure 4. Compressional velocity predicted for Grain shearing model, EDFM and Viscous grain shearing model using the parameters of Idukki Reservoir from site # 1-3.

The porosity, dry density and wet bulk density computations are carried out using pycnometer test in the laboratory. Low porosity in site #1 suggests that the sediment samples are compact and consolidated in nature. The wet bulk density of site #1 sample is 2.35 g/cm^3 which suggest that there is an overall reduction in porosity and void ratio in the measurements of sediments. Hence it is found to be highly consolidated and denser whereas sediments obtained from site # 2 and site # 3 is relatively disaggregated compared to site # 1 soil type.

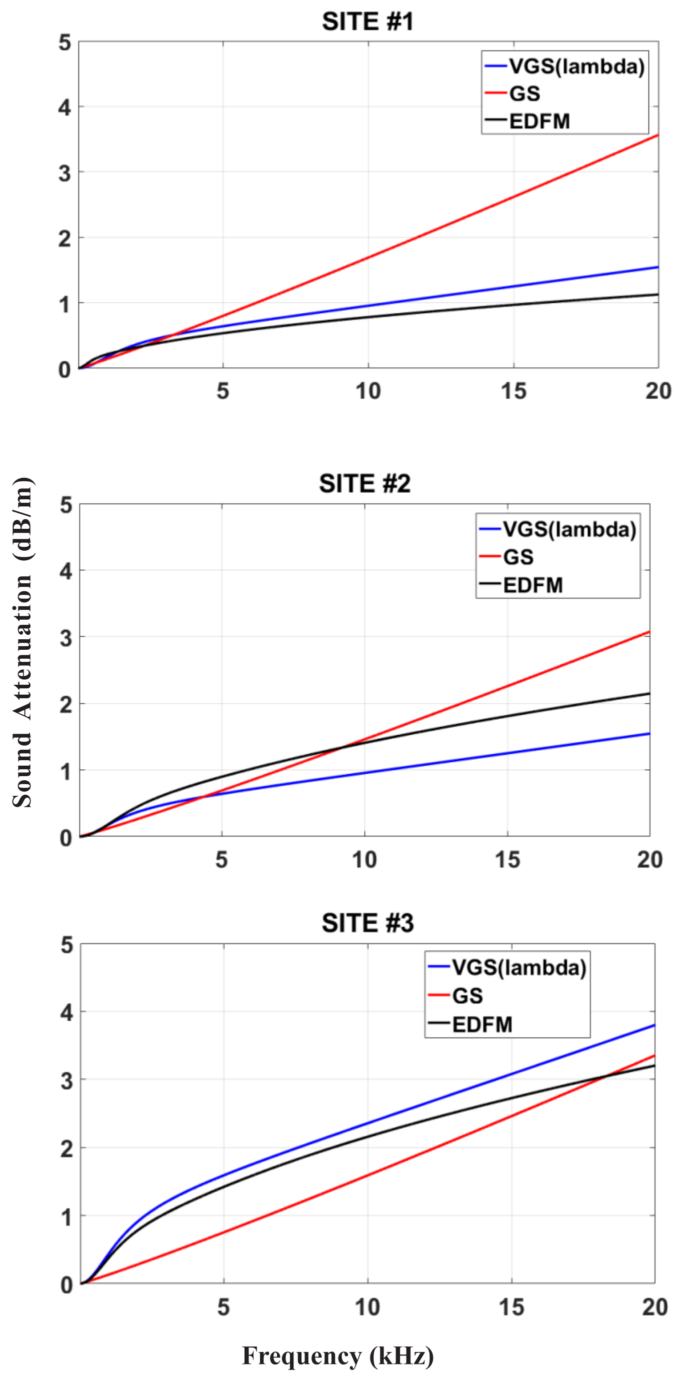

Figure 5. Compressional attenuation predicted for Grain shearing model, EDFM and Viscous grain shearing model using the parameters of Idukki Reservoir from site # 1-3.

4. IDUKKI RESERVOIR SEDIMENT COMPRESSIONAL VELOCITY AND ATTENUATION

The measurements of sound speed and attenuations in the Idukki reservoir for 3 various sites are estimated and the results are discussed. The results of compressional speed are shown in Fig. 4. The computation of sound speed as a function of frequency is calculated using effective density fluid model, grain shearing model and viscous grain shearing model.

For reference, the published results from SAX 99 are used as a benchmark for verification of the numerical implementation. SAX 99 is a high frequency sediment acoustics experiment which was conducted to determine the compressional velocity and the attenuation in the sandy sediments at a single site.

The compressional wave speed measurements fell within the ranges of 1600-2400 m/s. It is noted that in the site # 1 the compressional velocity is higher compared to the other 2 sites, possibly due to low porosity of the sediments. Published results also indicate that for low porosity the sound speed increases.

At site #1, the attenuation values are considerably lower as the sediment is denser and less porous. The attenuation appears to increase linearly with frequency. The G-S model predicts values close to 2 dB/(m.kHz) which is typical of coarse sandy sediments. The wave model predicts an attenuation range between 1 dB/(m.kHz) - 3 dB/(m.kHz) for the 3 sites. The attenuation is observed to be high for more porous sediment samples.

5. MODELLING OF TRANSMISSION LOSS IN SEDIMENTS

For modelling transmission loss, wavenumber integration technique is used in the frequency band of 5-15 kHz. The water column depth is taken as 50 m and the thickness of sediment layer is 20 m. Results of model run are obtained in the form of a color-contoured transmission loss (TL) mosaic as a function of depth and range.

5.1 RESULTS AND DISCUSSIONS

In the present analysis, the results of TL are presented for the site #1 and site #2 which show significant variation

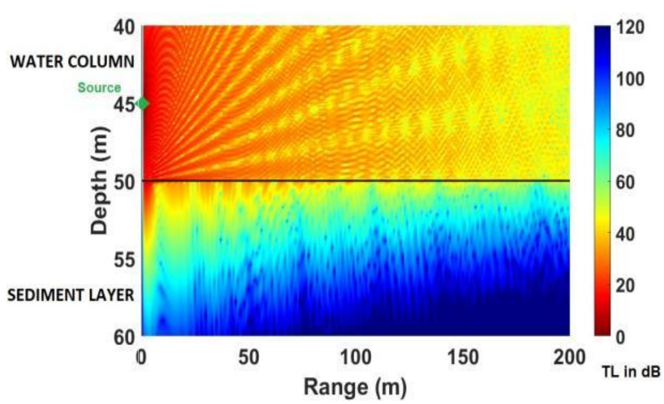

Figure 6. Modelled TL mosaic (5 kHz) for depth from 40-60 m out to a range of 200 m. The solid black line indicates the flat water-sediment interface. The source is located at a depth of 45 m from the sea surface in a water column of depth 50 m. The sediment type represents the data obtained at site # 1.

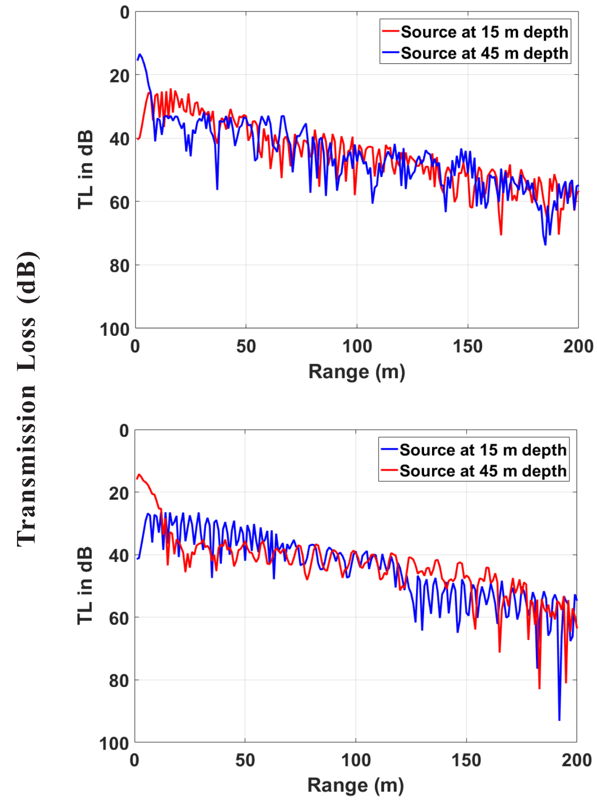

Figure 7. Modelled TL as a function of range for two source depths (15 m and 45 m). The water column depth is 50 m and the receiver is placed 1 m below the seafloor.

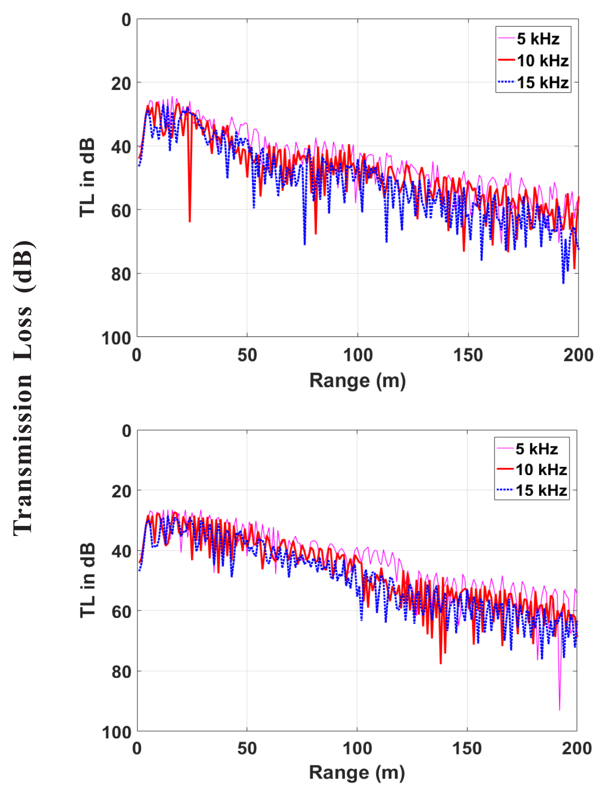

Figure 8. Modelled transmission loss as a function of range is compared for frequencies of 5, 10 and 15 kHz. The source depth is 15 m in a water column depth of 50 m. The receiver is placed 1 m below the seafloor.

in geoacoustic parameters. The parameters for sites 2 and 3 appear to be similar and hence only one is considered for modeling and interpretation of results. Modelled TL mosaic is shown in Fig. 6 for depth from 40-60 m out to a range of 200 m. The water column depth is taken as 50 m and the thickness of sediment layer is 20 m.

The results are compared in terms of transmission loss for variation with source depth, sediment type and frequency of operation. Results are generated at frequencies of 5, 10 and 15 kHz respectively.

5.1.1 Variation with Source Depth

TL results at 5 kHz are compared for two source depths, one at 45 m and the other at 15 m from the water surface in Fig. 7 for sites 1 and 2.

At 45 m depth, as the source is closer to the seafloor, the TL values are initially low but increases with increase in range. Similar effect is observed for both the sediment types. The TL fluctuation (at 5 kHz) appears to be higher in case of sandy bottom. TL increases with range and a TL of ~ 50 dB is observed at a range of 100 m from the source for both sediments and both for source depths. TL is found to increase with increase in the frequency of transmission as the depth of penetration decreases exponentially with increase in frequency (linearly in dB).

5.1.2 Variation with Frequency

The transmission loss is observed to increase gradually with increase in frequency from 5 to 15 kHz for both types of sediments. For site 1, at a range of 100 m and a receiver depth of 1 m below the water-sediment interface, the TL values increase from 45 dB at 5 kHz to 52 dB at 15 kHz. For site 2, at a range of 100 m TL values increase from 42 dB at 5 kHz to 58 dB at 15 kHz.

Comparison of TL results obtained at different frequencies in 5-15 kHz band indicates that the depth of penetration decreases exponentially (linearly in dB) with increase in the frequency of transmission. The TL values increase gradually with increase in frequency from 5 to 15 kHz for both types of sediments considered in the analysis.

It is expected that in field measurements, additional loss would be incurred due to scattering, both from rough seafloor and sediment volume inhomogeneities. Losses due to incoherent scattering depend on the wavelength of acoustic transmissions, the relative scales of bottom roughness and thickness of sediment layers. The compressional attenuation values typical of sandy and silty-clay sediments are used in the present analysis and assumed to be constant with increase in depth. However, these values change with increase in depth and need to be ascertained from *in situ* measurements.

6. SUMMARY AND CONCLUSIONS

In this paper, sediment samples collected from 3 different sites in the Idukki reservoir in Kerala are used to estimate the sediment characteristic types, geophysical and geoacoustic parameters. These physical components help to estimate compressional velocity and attenuation using established sediment wave theory models which includes effective density fluid model (EDFM), grain shearing model (GS) and viscous grain shearing model (VGS).

Sample statistics of site # 1 shows that the sediment is denser and less porous in nature and is classified as sandy very fine gravel type. The sample from site # 2 and site # 3 are similar in composition and belong to the same textural group of gravelly sand. Altogether, it is a mix of poorly sorted gravel and sand. For site #1 the compressional velocity predicted for EDFM, GS and VGS models ranges from 2300 m/s to 2500 m/s. For site # 2 and site # 3, range is between 1800 m/s to 2000 m/s. The low porosity of the sediment at site # 1 possibly may have contributed to the higher value of compressional velocity. The compressional attenuation ranges for the three models is between 1 dB/(m.kHz) - 3 dB/(m.kHz).

Subsequently transmission loss is modelled using wavenumber integration technique for a sediment section of depth 20 m and water column depth of 50 m. The results are compared in terms of variation with source depth 15 m, 45 m and frequency band of 5–15 kHz respectively. TL is found to increase linearly with frequency and decreases exponentially (linearly in dB) with the depth of penetration when varied depth wise. For site 1, at a range of 100 m and a receiver point of 1 m below the sediment bed, the TL values increase from 45 dB at 5 kHz to 52 dB at 15 kHz. For site 2, at a range of 100 m TL values increase from 42 dB at 5 kHz to 58 dB at 15 kHz. Therefore, it is observed that TL varies gradually with increase in frequency for both types of sediments.

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For the present work he has done supervision, visualization, conceptualization, data acquisition, writing-review-editing.

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In the current study, he was involved in the in-situ data acquisition and estimation of physical properties of marine sediments.