Report no. changed (Mar 2006): SM-218-UU

SACLANTCEN MEMORANDUM
serial no.: SM-218

SACLANT UNDERSEA RESEARCH CENTRE

MEMORANDUM

A note on attenuation and dispersion in marine sediments

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April 1989

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A note on attenuation and dispersion in marine sediments

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The content of this document pertains to work performed under Project 12 of the SACLANTCEN Programme of Work. The document has been approved for release by The Director, SACLANTCEN.

Issued by:
Underwater Research Division

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Executive Summary: Propagation loss is a critical factor for sonar performance. Low-frequency sound propagation loss is largely determined by acoustic attenuation in the sea bottom.

This memorandum is part of an ongoing project where the objective is to quantify the bottom loss in areas of operational interest, and to provide appropriate methods for acquisition of relevant bottom data. To achieve this objective it is essential to understand how sound interacts with sediments of different characteristics. This memorandum summarizes and discusses theoretical models of physical mechanisms that govern acoustic propagation in marine sediments, in particular the frequency dependence of attenuation and sound speed (i.e. dispersion).

Theoretical models predict that the most important contribution to intrinsic attenuation in water-saturated marine sediments is viscous loss caused by fluid motion relative to the solid-particle structure. At very low frequencies, friction of solid particles may also be an important loss mechanism. The relative contribution from the various factors is dependent on a large number of sediment properties, which are difficult to measure, and it is therefore difficult to predict how attenuation will vary with frequency. Fortunately the dispersion of sound speed will be small in all cases and of no practical consequence for sonar operations.

In a limited frequency interval it may be permissible to assume that attenuation increases linearly with frequency. Extrapolation of attenuation values over a large frequency interval is very difficult and it must be concluded that attenuation of the sea bed has to be measured at the actual sonar frequency range. This conclusion is an important consideration in the development of new techniques for direct and indirect measurements of sea-floor acoustic parameters and for the interpretation of the reults.

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A note on attenuation and dispersion in marine sediments

J.M. Hovem

Abstract: From the more recent investigations reported in the literature, it can be concluded that solid friction appears to be of little importance for attenuation in partially and fully saturated sediments and that the dominating loss mechanism is due to the flow of fluid relative to the solid. The complete Biot theory describes both the loss associated with the global flow of fluid, which is dependent on the permeability of the medium, and the local fluid flow caused by the opening and closing of cracks. This last contribution can be modelled by assuming a viscoelastic frame. The purpose of this note is to discuss some consequences of the theory, especially those concerning the frequency dependence of attenuation and sound velocity. It is demonstrated that the Biot theory does not give more velocity dispersion than expected from any causal linear system and that it is extremely difficult to use the theory for predicting how the attenuation will vary with frequency.

Keywords: attenuation ◦ Biot ◦ dispersion ◦ fluid flow ◦ permeability ◦ sediments ◦ solid friction ◦ velocity

Contents

1
Introduction

Physical understanding and modelling of acoustic and seismic attenuation in marine sediments and rocks are important for predicting long-range sonar propagation. For the low frequencies being used in these applications, it is difficult to obtain attenuation values under controlled conditions; and it is, therefore, desirable to extrapolate the low frequency values from measurements at higher frequencies. This requires an understanding of the physical processes involved and knowledge about the frequency dependence of attenuation. The models for attenuation which have been discussed most frequently in the literature are the solid friction model and various viscoelastic models where the attenuation is caused by a flow of a viscous fluid relative to the solid. Chemical effects, which are also important in some cases, have not been treated in the same detail. A major problem with all loss models is that it is difficult to determine the values of the parameters by independent measurements. Hence, it is difficult to decide which mechanism is the most important and to predict the attenuation based on the knowledge of the physical composition of the material.

The purpose with this note is to comment on some of the most well-known loss models and to point out their most important characteristics. The many papers of Biot and Stoll on the subject of fluid induced attenuation, as well as the papers by Hamilton, are referenced. Useful reviews of attenuation of seismic waves in rocks have been given by Bourbie (1984, 1985), Mavko and Nur (1979), Toksöz et al. (1979) and Johnston et al. (1979).

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Definitions

The loss models will normally result in an elastic modulus M (bulk or shear) being a complex function of frequency:

$$M(\omega) = M_{\mathrm{r}}(\omega) + iM_{\mathrm{i}}(\omega). \tag{1}$$

There are several definitions of the Q-value; here the following definition is used:

$$Q(\omega) = M_{\mathrm{r}}(\omega)/M_{\mathrm{i}}(\omega). \tag{2}$$

The velocity v and the attenuation α are found by solving the following equation:

$$\left(\frac{1}{v} - i\frac{\alpha}{\omega}\right)^2 = \frac{\rho}{M(\omega)} \tag{3}$$

with the solutions

$$\alpha = \omega\sqrt{\frac{\rho[|M(\omega)| - M_{\mathrm{r}}(\omega)]}{2|M(\omega)|^2}}, \tag{4}$$

$$v = \sqrt{\frac{2|M(\omega)|^2}{\rho[M(\omega) + M_{\mathrm{r}}(\omega)]}}. \tag{5}$$

When the losses are small, good approximations to these solutions are

$$v \approx \sqrt{M_{\mathrm{r}}(\omega)/\rho}, \tag{6}$$

$$\alpha = \frac{\omega}{2v}\frac{M_{\mathrm{i}}(\omega)}{M_{\mathrm{r}}(\omega)} = \frac{\omega}{2v}Q^{-1}(\omega). \tag{7}$$

For linear causal systems there is a relation between attenuation and velocity given by the so-called Kramers–Kröning equation (White, 1983, p. 87; Aki and Richards, 1980, p. 167; and Futterman, 1962). This relation shows that attenuation is always accompanied by velocity dispersion, although the dispersion may be very weak and difficult to determine experimentally. Only a lossless medium can have a velocity constant with frequency.

Experimental observation of attenuation in sediments often seems to indicate that the Q-value is constant and attenuation is increasing linearly with frequency. Therefore, it is interesting to discuss the consequences of the constant Q assumption.

An arbitrary good approximation to a constant Q can be obtained by a combination of simple models with different and staggered critical frequencies, as will be discussed later. Kjartanson (1979) found that the physically realisable constant-Q model will have the complex modulus

$$M(\omega) = M_0(i\omega/\omega_0)^{2\gamma} \tag{8}$$

with the sound velocity v and Q-value given by

$$v = v_0 \left|\omega/\omega_0\right|^{\gamma}, \tag{9}$$

$$Q = \tan^{-1}(\pi\gamma), \tag{10}$$

where ω_0 is an arbitrary frequency where the sound velocity is v_0. The velocity dispersion of the constant-Q model is shown in Fig. 1 for some values of Q. The dispersion for a medium with $Q = 30$ is, for instance, a total of 5% over a frequency band of two decades.

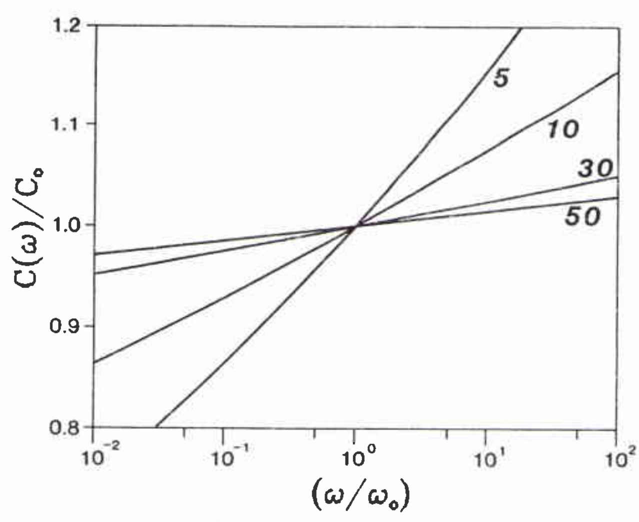

Fig. 1. Velocity dispersion for the constant-Q model for $Q = 5$, 10, 30, 50.

If the velocity dispersion is neglected, the time response becomes non-causal (Liu et al. 1976). As an example, the impulse response of a medium with constant Q

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and velocity v after a distance x is given by

$$h(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \exp\left[-|\omega| x/2vQ\right] \exp[i\omega(t - x/v)]\, \mathrm{d}\omega,$$

$$h(t) = \frac{1}{\pi} \frac{(x/2vQ)}{(x/2vQ)^2 + (x/v - t)^2}.$$

The response is symmetric about the nominal arrival time $t = x/v$.

3

Solid friction model

While the solid friction model is quite widely accepted by acousticians and geophysicists, the model has defects and many investigations have cast doubt on the importance of solid friction as a major source of attenuation in saturated and partially saturated sediments.

Attenuation caused by friction, mostly in rocks in relation to seismology and seismic exploration, has been investigated by White (1966), Walsh (1966), and Johnston et al. (1979). Experimental studies have been done by Winkler and Nur (1982) and Stewert et al. (1983). A fairly general conclusion from these studies is that the Q-value appears to be independent of strain amplitude for strains lower than about 10^{-6}. Measurements in dry materials (rocks) also show very low attenuation, typically Q-values greater than 100.

Solid friction, as for instance that caused by sliding between particles in contacts, is normally accounted for by letting the elastic moduli become complex. In terms of the Lamé parameters λ and μ the ordinary parameter is replaced by

$$\lambda = \lambda + i\lambda', \qquad \mu = \mu + i\mu'. \tag{12}$$

The result is that the elastic moduli (shear or bulk) become complex constants independent of frequency. This means that the attenuation coefficients are increasing linearly with frequency and that the wave velocities are constant.

The solid friction model is simple to use in calculations, and the constant-Q feature and the absence of dispersion are claimed by many to be in agreement with experimental observations of attenuation in marine sediments (Hamilton, 1972, 1976, 1980). This statement has, however, been challenged by others (Stoll, 1985).

Two features of the solid friction model should be noted:

- First, because friction is a nonlinear process, the velocity and attenuation will in principle be dependent on the amplitude and the waveform of the strain. Strictly speaking, the superposition principle is not valid, and the decomposition of a time domain signal into the frequency domain by Fourier transform is not allowed. For a single frequency and for low strains as noted above, this may from a practical point of view not be a serious restriction on the validity of the model.

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- Secondly, a model with constant Q and no velocity dispersion is not obeying the causality principle, as discussed before. For a single-frequency component this is of no consequence, but it could be important when attempting to compute the time domain responses in a high-loss medium.

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Viscoelastic models

In the viscoelastic models it is assumed that not only the stresses and strains are involved but also their derivative with respect to time. One model, for instance, assumes that the stress $s(t)$ is given by the strain $e(t)$ and its derivative with respect to time $\dot{e}(t)$ by

$$s(t) = Ke(t) + N\dot{e}(t), \tag{13}$$

where K is the elastic element and N is a viscous element given by the fluid viscosity and the geometry of the pores and voids of the material. In an equivalent circuit description the elastic element is represented by a spring and the viscous element with a dashpot.

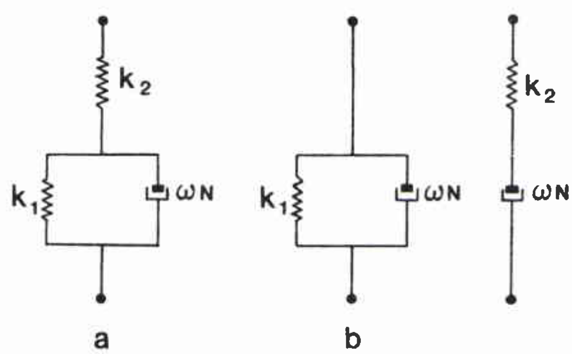

Fig. 2. Viscoelastic elements: (a) standard 3-parameter model, (b) Voigt model, (c) Maxwell model.

The standard 3-parameter model shown in Fig. 2a is frequently used for representing a composite medium. It is composed of a spring in series with a parallel combination of a spring and a dashpot. The total complex modulus is, therefore, given by

$$M_3^{-1}(\omega) = K_2^{-1} + (K_1 + i\omega N)^{-1}. \tag{14}$$

The Voigt model is obtained when $K_2 \to \infty$:

$$M_1(\omega) = (K_1 + i\omega N). \tag{15}$$

The Maxwell element is the limiting case for $K_1 = 0$:

$$M_2 = \frac{i\omega N K_2}{K_2 + i\omega N}. \tag{16}$$

These elements are shown in Figs. 2b,c.

In the low-loss case $M_\text{i} \ll M_\text{r}$ and approximately

$$v(\omega) = \sqrt{\frac{1}{\rho}\left(\frac{K_1 K_2}{K_1 + K_2}\right)\frac{1 + (\omega N)^2/K_1(K_1 + K_2)}{1 + (\omega N)^2/(K_1 + K_2)^2}}, \tag{17}$$

$$Q(\omega) = \frac{K_1(K_1 + K_2)}{K_2}\left(\frac{1}{\omega N}\right) + \frac{\omega N}{K_2}. \tag{18}$$

Figure 3 shows Q-value and velocity as the function of frequency for the standard 3-parameter model. At low frequencies the Q is proportional with frequency, and the attenuation coefficient is proportional with frequency, squared. At high frequencies Q is proportional to frequency and attenuation is constant with frequency. The frequency where Q is minimum is given by

$$\omega_0 = \frac{1}{N}\sqrt{K_1(K_1 + K_2)}. \tag{19}$$

The Voigt model is elastic at low frequency and viscous at high frequency, and attenuation is proportional to frequency squared. The Maxwell is viscous at low frequency and elastic at high frequency, and the attenuation is nearly constant with frequency.

The response $e(t)$ to a step in $\sigma(t)$ at $t = 0$ is called the creep function (Lomnitz, 1957). When the height of the step in stress is σ_0 the creep function for the general 3-parameter model is

$$\phi(t) = \frac{\sigma_0}{K_2} + \frac{\sigma_0}{K_1}\left(1 - \exp\left[K_1 t/N\right]\right). \tag{20}$$

It is quite clear that any physically allowed creep function must be a causal function.

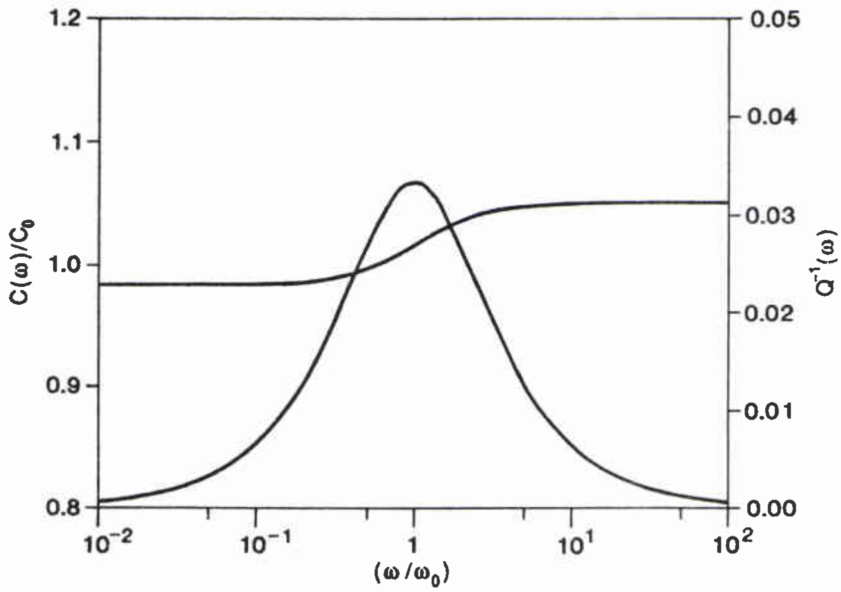

Fig. 3. Q-value and velocity for the standard 3-parameter viscoelastic model as functions of frequency.

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Fluid loss models

The effect of a pore fluid on wave velocities and attenuation has been investigated by Toksöz et al. (1979) and Johnston et al. (1979). Murphy (1982) in particular has conducted a most interesting study of the effect of partial water saturation on the attenuation and velocity in porous sandstone. He concluded that at saturation levels lower than 0.01 (very dry) the energy losses can be attributed to micro capillary hysteresis but that the attenuation is very low. At saturations higher than 0.02 and towards full saturation, different mechanisms take control; and Murphy concludes that attenuation then is caused by fluid flow. Since other investigations point in the same direction (Stoll, 1985), there is no reason to doubt that the pore fluid plays a dominating role in the attenuation of low-amplitude acoustic and seismic waves.

There are at least two mechanisms for viscous dissipation resulting from wave-induced pore fluid flow. The first mechanism is caused by the overall motion of fluid relative to the skeleton frame, and attenuation depends on the permeability of the medium and the geometry and turtuosity of the pores. This effect is believed to be important in highly permeable and coarse materials.

The other mechanism, known as the squirt or squish, is due to local fluid flow caused by the compressions of grains and fine capillaries. This effect is thought to be important in finer sediments where the permeability is low even if the porosity is high.

The theoretical foundation for the description of both mechanisms was first given by Biot in a series of papers, and later Stoll expanded on them and made the theory more applicable. The Biot theory is really a viscoelastic theory with the addition of the effect of fluid inertia. Since the theory is now well known, it will not be discussed in detail here; but certain features that are sometimes overlooked will be discussed.

In his first two papers on the subject Biot (1956, I & II) presented a theory for the viscous attenuation caused by an overall fluid flow. The model predicts an attenuation which is increasing with frequency squared at low frequency and as the square root of frequency at higher frequencies. Figure 4a presents one example of attenuation of the standard Biot theory for the parameters given in Table 1. This particular example gives a minimum Q-value of about 50. Figure 4b shows the velocity predicted by the Biot theory for the same parameters together with the expected velocity dispersion of the constant-Q model (7, 8) calculated for $Q = 50$.

It is evident that the dispersion given by the Biot model is not more than expected for a linear causal system.

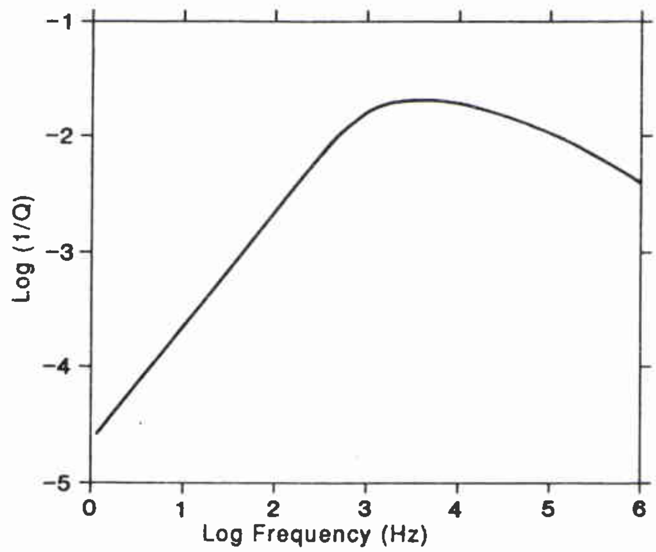

Fig. 4a. Q-value as function of frequency calculated by the Biot model with the parameters given in Table 1.

Table 1
Physical parameters used for input to the Biot theory to produce Fig. 4

Parameter	Value	Units
bulk modulus of solid, K_s	38.0×10^9	Pa
bulk modulus of fluid, K_f	2.15×10^9	Pa
bulk modulus of frame, K_b	0.6×10^9	Pa
shear modulus of frame, μ	0.6×10^9	Pa
fluid density, ρ_f	1.0×10^3	kg/m^3
solid density, ρ_s	2.5×10^3	kg/m^3
porosity, Φ	0.37	–
fluid viscosity, η	0.10	Pa s
permeability, B	0.23×10^{-10}	m^2
pore size parameter, a_p	3.5×10^{-5}	m

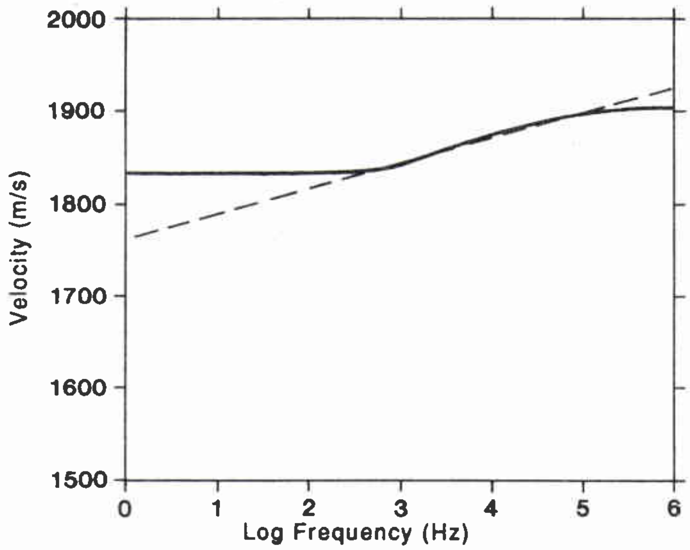

Fig. 4b. Velocity dispersion for the Biot model (solid curve) calculated with the parameters given in Table 1 and for the constant-Q model (broken curve) with $Q = 50$.

The transition between low and high frequency is given by a critical frequency ω_c:

$$\omega_c = \frac{1}{a_p^2}\frac{\eta}{\rho_f}, \tag{21}$$

where η and ρ_f is the fluid viscosity and density, respectively, and a_p is a pore size parameter as a characteristic measure of the size of the pores. Biot found that for circular pores a_p is equal to the radius and for slits equal to 2/3 times the slit separation. When applying the Biot theory to real sediments, the choice of a_p is of extreme importance for the frequency dependence of the viscous attenuation curve. Which value to use in real cases has been discussed quite extensively in the literature, and the consensus seems to be that a_p should be related to the average size of the grains and should also be proportional to the square root of the permeability.

Since there is only one parameter for the pore size in the theory, it can be argued that it can only be valid in very uniform media where all the pores have essentially the same geometry and size. In real media there is likely to be a distribution of pore sizes, and one will expect to have a more linear increase with frequency at least over a limited band of frequencies. In principle, one could modify the theory to allow for a distribution of grain sizes and pores and, in fact, such a modification has been made by McCann and McCann (1985). With a particular assumed pore size distribution they obtain, as expected, an essentially linear attenuation law. The problem with the approach is that one needs to know the relationship between the grain size and pore size distribution and the permeability. This information is in general not available. However, it shows at least that it is principally and physically possible to have a viscous loss increasing linearly with frequency.

The effect of a local flow of fluid caused by the compression of grains and capillaries was also considered by Biot (1962) in an extension of his first theory. He proposed then that the bulk modulus of the frame (K_b) for the porous medium can be modelled as a standard 3-parameter element as discussed earlier:

$$\frac{1}{K_b} = \frac{1}{K_0} + \frac{1}{K_1 + i\omega N}. \tag{22}$$

Biot showed that a gap representing a pore to a first approximation is purely viscous, and he found that a gap of length L and height h has

$$N = \frac{12}{\pi}\frac{\eta L^2}{h^2}. \tag{23}$$

Stoll (1979) gave for spherical grains of diameter D in contact with particle separation h at points of closest contact:

$$N = \frac{3\pi}{8}\frac{\eta D}{h}. \tag{24}$$

The modulus K_0 is the stiffness of the solid grains and K_1 represents the stiffness of the grain contacts plus the incompressibility of the fluid between the grains. Since $K_0 \gg K_1$ the frame can with good approximation be modelled as a standard Voigt element with

$$K_b = K_1 + i\omega N. \tag{25}$$

In practice there will be spectrum of pore sizes and shapes.

The complete theory as outlined above can then account for the viscous attenuation caused by both the local and the global flow of fluid. In addition, one can, if one wants, add a small imaginary constant to K_b to allow for some frictional loss.

While the Biot theory gives a good insight into how the fluid is affecting sound velocity and attenuation, the theory requires input values for a great number of parameters which cannot be obtained from independent measurements. It is, therefore, difficult to use the theory to arrive at a general conclusion as to how attenuation will vary with frequency.

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Summary and conclusions

In this note some of the more common models for sound speed and attenuation in marine sediments have been discussed. The purpose was not to describe the models in full, but rather to point to features that are sometimes overlooked.

It can be concluded from the more recent investigations that solid friction appears to be of rather little importance for attenuation in partially and fully saturated sediments and that the dominating loss mechanism is due to the flow of fluid relative to the solid. The complete Biot theory describes both the loss associated with the global flow of fluid, which is dependent on the permeability of the medium, and the local fluid flow caused by the opening and closing of cracks. This last contribution can be modelled by assuming a viscoelastic frame.

It has been demonstrated that the Biot theory does not give more velocity dispersion than expected from any causal linear system.

The theory depends on a great many parameters that are unknown and for this reason it is difficult to use the theory for predicting attenuation and velocity. It is also difficult to make general statements regarding the frequency dependence of attenuation and even the viscous term can give almost a linear frequency law over a limited frequency band of observation.

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