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Model-data comparison of high frequency compressional wave attenuation in water-saturated granular medium with bimodal grain size distribution

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ABSTRACT

Several acoustic models, such as the poro-elastic model, visco-elastic model, and multiple scattering model, have been used for describing the dispersion relation in a porous granular medium. However, these models are based on continuum or scattering theory, and therefore cannot explain the broadband measurements in cases where scattering and non-scattering losses co-exist. Additionally, since the models assume that the porous granular medium consists of grains of identical size (unimodal size distribution), the models does not account for the behavior of wave dispersion in a medium that has a distribution of differing grain sizes. As an alternative approach, this study proposes a new broadband attenuation model that describes the high frequency dispersion relation for the p-wave in the case of elastic grain scatterers existing in the background fluid medium. The broadband model combines the Biot-Stoll plus grain contact squirt and shear flow (BICSQS) model and the quasicrystalline approximation (QCA) multiple scattering model. Additionally, distribution of grain size effect is examined rudimentarily through consideration of bimodal grain size distribution. Through the quantitative analysis of the broadband model and measured data, it is shown that the model can explain the attenuation dependencies of frequency and grain size distribution for a water-saturated granular medium in the frequency range from 350 kHz to 1.1 MHz. This study can be applied to the high frequency acoustic SONAR modeling and design in the water-saturated environment.

1. Introduction

Dispersion relation for compressional wave (p-wave) speed and attenuation in the ocean sediment have been studied for some time in underwater acoustics [1,2]. In particular, the relation between the geophysical and acoustical properties of ocean sediment have been investigated through experimental and theoretical works [3,4]. In a recent series of articles, experiments were carried out in a water-saturated granular medium with varying grain size and in a variety of frequency ranges since the p-wave speed and attenuation for water-saturated granular medium depend heavily on both the frequency and grain size [5–7]. In many of these studies, the mean grain size is adopted as a conventional indicator to classify the geophysical property of the ocean sediment [5–8]. However, the dispersion relation of the medium can vary with regard to the grain size distribution [8]. In particular, bimodal grain size distribution has been observed in several sediments [9,10]. While a few acoustic experiments have reported a difference between the dispersion relation in the porous granular medium with bimodal grain size distribution and that with the identical size (unimodal) distribution [11], very little is known about the phenomenon for sediment acoustic models.

To describe the dispersion relation in the water-saturated granular medium, many sediment acoustic models have been developed [12–14]. In the low-mid frequency range (1–10 kHz), continuum theories, such as the poro-elastic model [12–14], have been applied to explain the experimental results [2,6]. However, in the higher frequencies, since the wave scattering effect becomes significant on the wave propagation [5–7], multiple scattering by particles has been used to model the high frequency characteristics of the granular medium [8,15,16]. Particularly, in the transition region, it can be assumed that both the scattering and non-scattering (such as viscous) losses have an important effect on wave propagation. While recent work showed a corrected

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poro-elastic model for multiple scattering effects that explains the broadband dispersion data [6], an empirical formula was used for multiple scattering, and the work was not derived from a model based on the physics of high frequency wave characteristics.

In this study, a new broadband attenuation model for a porous granular medium with bimodal grain size distribution is developed in the global frequency range. The bimodal granular medium can be considered as a medium in which the scattering and non-scattering losses coexist. First, several sediment acoustic models, including poro-elastic models and multiple scattering models, are discussed with the measured data for a bimodal granular medium. Second, based on the comparisons of the model and data, baseline models for the development of the broadband model are selected and modified, considering the bimodal grain size distribution. Finally, the attenuation calculation predicted by the new broadband model is compared with the measured data.

Section 2 briefly summarizes glass beads data including media with unimodal and bimodal grain size distributions. In Section 3, several sediment acoustic models are compared with the glass beads data. Section 4 shows the procedure of the development of the new broadband attenuation model for bimodal grain size distribution. In Section 5, a comparison with the broadband model and data is presented and discussed. Section 6 concludes the present study.

2. Glass beads experiment

Yang et al. [11] carried out high frequency measurements of compressional wave speed and attenuation in a water-saturated granular medium with unimodal and bimodal grain size distribution. Soda lime silica glass beads with mean grain sizes of 375 μm (S3) and 625 μm (S5) were employed. According to the Udden-Wentworth size classes [4], S3 and S5 represent the medium sand and coarse sand, respectively. Three kinds of glass bead samples (S35) were composed by mixing S3 and S5 at the following volume ratios: 7:3, 5:5, and 3:7. The geophysical properties of the glass bead samples are listed in Table 1. The porosities of the glass beads samples were estimated by using pycnometer which is used for density analysis.

The experimental setup is shown in Fig. 1. An acrylic box containing glass bead samples was located in the middle of a water tank. Two boxes, having dimensions of 10 cm × 20 cm × 20 cm and 20 cm × 20 cm × 20 cm with a 0.5 cm thickness, were used for the measurement. Two pairs of ultrasonic transducers (Panametrics V301 and V302) were employed for broadband measurements (Table 2). The central frequencies of the transducers are 500 kHz (V301) and 1 MHz (V302). The distance between the source and sediment sample was much larger than the near-field distance; therefore, our experimental setup satisfied the far-field condition. The effect of the acrylic box on the received signals is eliminated by calibration using the two boxes employing the receiver-to-receiver spectral ratio. The slightly dispersed received signals were observed compared with the received signal passing through just water, and the time-domain signal magnitude decreased by around thirty percent. The frequency spectrum of the signal passing through the acrylic box was also reduced by thirty percent compared with the signal passing through just water, but the shapes of the frequency responses of the received signals passing through just water and the box did not differ from each other.

A 1-cycle sine pulse was chosen as the source signal. This source pulse was transmitted by a waveform generator (Agilent 33250A), then amplified to 40 dB in order to obtain high signal-to-noise (SNR) ratio. The received signal was digitized by an oscilloscope (LeCroy 9310CM) and the data was saved on a computer.

The sound speed was obtained using the following equation [17]:

$$c_p = \frac{\omega d_s}{2\pi n + \Delta\phi - \omega d_w / c_w}, \tag{1}$$

where ω is the angular frequency, $d_s = r_{s2} - r_{s1}$, r_{s1} and r_{s2} are 0.1 m and 0.2 m, respectively, n is the wrapping number added to the wrapped phase delay at frequencies when the discontinuity of phase appears, d_w is equal to 0.1 m, and c_w is the sound speed in

Table 1
Geophysical properties of the glass bead samples.

Parameters	Symbol	S3	S35 (7:3)	S35 (5:5)	S35 (3:7)	S5
Mean diameter (μm)	d	375	450	500	550	625
Porosity	β	0.412	0.376	0.365	0.364	0.41
Density (kg/m³)	ρ	2500	2500	2500	2500	2500

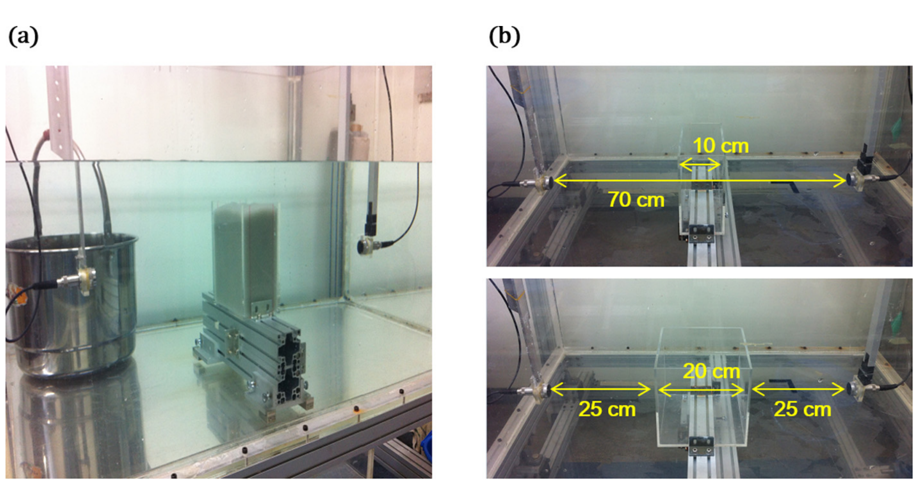

Fig. 1. (a) Photograph of the experimental setup. (b) Dimensions of the apparatus with empty boxes.