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Multiscale analysis of waves reflected by granular media: Acoustic experiments on glass beads and effective medium theories

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[1] The avelet response is a multiscale method based on the continuous avelet transform. We use it to characterize the acoustic reflectivit of a la er of glass beads ith diameter $d = 1$ mm randoml arranged in ater. The volumetric concentration is f $\simeq 63\%$ of spherical inclusions. The avelet response is measured over a large frequenc range (100 kHz $\leq f \leq$ 5 MHz) here five different acoustic regimes are identified on the basis of scattering phenomena. A strong decrease in the reflectivit occurs hen the avelength of the incident ave is t ice the bead diameter, a situation here lateral scattering is dominant. The energ ratio of the ballistic and the coda parts of the avelet response reveals a clear transition from a ballistic propagation regime to a diffusion regime here multiple scattering occurs. The e perimental data are e plained ith an effective medium theor approach: the reflectivit data in the lo -frequenc domain of the spanned frequenc range are correctl reproduced ith quasi-static models. For higher frequencies, more sophisticated models accounting for multiple scattering must be used. The high-frequenc part of the e perimental reflectivit curve ma be e plained b strong multiple scattering at the top of the glass beads located at the surface of the la er and corresponds to the optical geometric limit.

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1. Introduction

[2] The nondestructive characterization of heterogeneous geological materials ith either seismic or electromagnetic aves is an important issue hich has motivated numerous studies concerned ith the heterogeneous properties of the Earth from the global scale [*Wysession et al.*, 1992; *Chambers et al.*, 2005] do n to the ver small scales encountered in environmental and engineering applications [*Exon et al.*, 1998; *Pecher et al.*, 2003]. Near-surface la ers also constitute an increasing matter of interest for either pollution concerns or safet assessment of civil engineering equipments. An e ample pertaining to the civil engineering industr concerns the characterization of the sea bottom [*Schock et al.*, 1989; *De Moustier and Matsumoto*, 1993; *Augustin et al.*, 1996; *Orange et al.*, 2002; *Acosta et al.*, 2004] for the purpose of planning the installation of optic fiber net orks and communication cables or to identif resources for future mining and fishing facilities [*Carter*, 1992; *McClatchie et al.*, 2000; *Kostylev et al.*, 2001].

[3] Acoustic probing of heterogeneous interfaces requires a good kno ledge of ave propagation inside the structures here strong interactions bet een the acoustic ave and the medium heterogeneities can occur. The interpretation of these phenomena is not straightfor ard: geological reflectors are comple , multiphase interfaces (i.e., mi tures of fluids, rocks and gas). For instance, the seafloor consists of different sedimental components (e.g., mud, silt, sand, lava) mi ed ith ater, constituting heterogeneous substrates [*Goff et al.*, 2000; *Le Gonidec et al.*, 2005]. The main ph sical parameters derived from echo sounder data are the velocit and the attenuation of the coherent aves, i.e., the specular reflections. Attenuation of broadband Chirp signals is used for sediment classification [*Vandenplas et al.*, 2000; *Stevenson et al.*, 2002; *Gutowski et al.*, 2002]. Attenuation is frequenc -dependent, and ne acoustic techniques use multifrequenc methods [*Vanneste et al.*, 2001; *Walter et al.*, 2002; *Lambert et al.*, 2002; *Price*, 2006].

[4] Wave propagation inside comple media has been intensivel described and has motivated numerous studies [e.g., *O'Doherty and Anstey*, 1971; *Sheng et al.*, 1986; *Burridge et al.*, 1988, 1993; *Scales*, 1993; *Page et al.*, 1995; *Cowan et al.*, 1998; *Derode et al.*, 1998; *Tournat et al.*, 2004; *Marchetti et al.*, 2004; *Dineva et al.*, 2006]. The interaction of the acoustic ave ith a comple interface is strongl controlled b the ratio l/d of the incident avelength to the heterogeneit size [*Le Gonidec et al.*, 2002]: At the macroscopic scale, hen the avelength l is much

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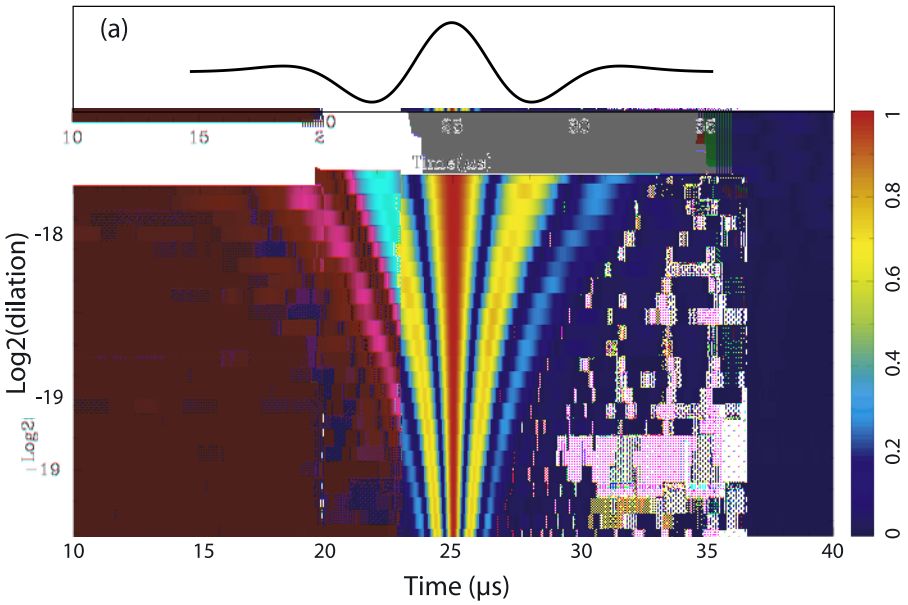


Figure 1. (a) One member of the e perimental avelet famil . Each avelet is inverted in order to best fit ith the fourth derivative of a Gaussian: $(d^4/dt^4)e\ p(-t^2)$. (b) Assemblage of the hole e perimental avelet famil obtained b ranking each avelet ith respect to its dilation inversel proportional to its central frequenc .

larger than the microstructure characteristic si**z**e d, the Ra leigh regime dominates and static effective medium theories provide a useful frame ork to derive the macroscopic properties of composite materials [e.g., *Chýlek et al.*, 2000]. Such static methods describe the frequenc -independent properties of the equivalent homogeneous medium and has been studied b man authors [*Foldy*, 1945; *Hashin and Shtrikman*, 1963; *Kuster and Toksöz*, 1974; *Berryman*, 1980; *Berryman and Berge*, 1996; *Aristégui and Angel*, 2002]. In the mesoscale domain here $l \simeq d$, the interaction bet een the acoustic ave and the microstructure of the medium strongl depends on the ratio l/d, and d namic effective medium theories have been proposed to account for both the frequenc -dependent properties of multiphase composites and multiple scattering [*Waterman and Truell*, 1961; *Sheng*, 1995; *Busch and Soukoulis*, 1996].

[5] In the present paper, e stud the frequenc dependence of the acoustic reflectivit of a la er made of a densel packed granular medium. In particular, e e amine the influence of the ratio l/d b means of the " avelet response" introduced in a previous paper [*Le Gonidec et al.*, 2002]. Similar to the continuous avelet transform, defined as the convolution bet een the anal **z**ed signal and a famil of avelets obtained from a given anal **z**ing function (see *Holschneider* [1995] for an introduction), the avelet response also uses a famil of avelets hich are propagated (NOT convolved) through the medium to be anal **z**ed. The properties of the avelet transform concerning the characteri**z**ation of abrupt changes in signals [e.g., *Mallat and Hwang*, 1992; *Herrmann*, 1994; *Alexandrescu et al.*, 1995, 1996] are retrieved in the avelet response. This method ma therefore be used to remotel probe the multiscale structure of comple interfaces [*Herrmann and Staal*, 1996; *Wapenaar*, 1998, 1999; *Marsan and Bean*, 1999] and more generall of heterogeneous structures. When compared to other anal **z**ing methods, the avelet response characteri**z**es the multiscale interface structure over a ver large dilation range both in the time and frequenc domains.

[6] In section 1, e recall the main steps of the avelet response method and e present the acoustic e periments. We measure the avelet response of a biphase composite medium made of a dense packing of glass beads surrounded b fluid. We anal **z**e the acoustic response of the granular medium from the avelet response data, and e identif five characteristic frequenc ranges. In section 2, e discuss the observed macroscopic effects from a microscale point of vie . We sho that the scattering diagram of a single glass bead can e plain the acoustic response of the granular medium. We put in evidence the propagation-to-diffusion transition. Sections 3 and 4, e introduce and compare effective medium theories ith the e perimental data. We define the frequenc ranges here the theories agree ith the data and discuss the results.

2. Acoustic Reflectivity of a Layer of Glass Beads

2.1. Principles of the Method and Experiments

[7] In order to anal **z**e the acoustic response of a granular medium, e use the avelet response method, a multiscale anal sis technique based on the continuous avelet transform introduced in details in previous papers [*Le Gonidec et al.*, 2002, 2003]. The main idea at the basis of the avelet response is to use a famil of incident aves hose source signals constitute a avelet famil as sho n in Figure 1 (i.e., a set of signals ith constant shape and different durations). The e perimental avelet famil is obtained b simulated annealing [*Conil et al.*, 2004]. The advantage of this method is to span a ide frequenc range hile keeping a good temporal locali**z**ation of the source signals, this allo s an optimal identification of the signals reflected

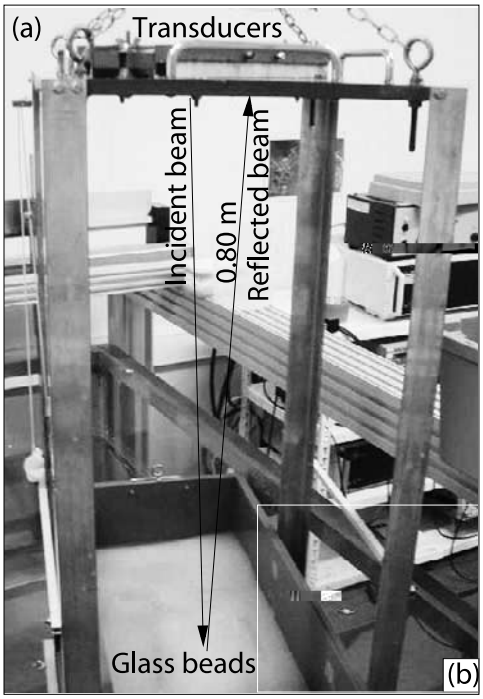


Figure 2. (a) Experimental setup holding two piezoelectric transducers above a rolling box filled with glass beads. The box can be horizontally translated while stacking the reflected signals in order to record the mean field. (b) Monodisperse glass beads randomly distributed in water. The concentration $f \simeq 0.63$ roughly corresponds to 10^9 beads/m^3 for $d = 1$ mm.

box the target, both in time and frequency domains. Another advantage is to avoid postprocessing operations like noise-sensitive deconvolution as often required in more conventional methods where the source signals are not controlled. The wavelet response has the further advantage to determine the homogeneity degree of a target geometry in terms of discontinuities. This has been described in previous papers [*Le Gonidec et al.*, 2002, 2003] where planar interfaces can be assimilated to Dirac-like and Heaviside-like discontinuities at low and high frequencies, respectively. A detailed account of the properties of the wavelet transform with respect to homogeneous functions is given by *Mallat and Hwang* [1992] and by *Alexandrescu et al.* [1995, 1996] for geophysical applications.

[8] The wavelet family used in the present study consists in 30 wavelets (Figure 1b) spanning a frequency range going from 200 kHz to 1 MHz. It has been generated by means of four pairs of transducers with central frequencies of 250, 500, 750, and 1000 kHz. The analyzing wavelet is the fourth derivative of a Gaussian function (Figure 1a) in order to have a well-defined central frequency while being sufficiently localized in time.

[9] The experimental setup shown in Figure 2 has already been discussed in details by *Le Gonidec et al.* [2002]. It consists in a rigid frame holding two transducers mounted in the normal incidence configuration, one for the emission and one for the reception. The acoustic reflector is a granular medium composed of a thick layer of glass beads. Both the transducers and the medium are immersed in the water of an acoustic tank. The medium is roughly 60 cm below the transducers and can be translated in order to measure the mean acoustic field in the far-field conditions. The experimental wavelet response of the medium is constructed by successively emitting each source signal (i.e., wavelet) and averaging the reflected signals.

[10] The glass beads of the granular medium are densely packed in a box, and the porosity derived from mass measurements is 37%. The concentration of the glass beads is $f \simeq 63\%$, typical of a random close packing [*Page et al.*, 1995, 1996] and significantly smaller than the densest concentration of 74% corresponding to a face-centered cubic packing of spherical inclusions [*Neser et al.*, 1997].

[11] A relevant nondimensional control parameter of the experiment is the ratio λ/d between the incident wavelength λ to the bead diameter d. Indeed, the granular media used in the present study have a porosity independent of the bead diameter and experimentally measured around 37% for all glass bead diameters. Then, the acoustic response of a granular medium only depends on the ratio λ/d: the glass beads are monodisperse and uniformly packed, so the wavelet responses measured for different bead diameters d may be rescaled to a common diameter and merged to obtain a global wavelet response spanning a wider range of the λ/d ratio. The wavelet response is measured for six different granular media with bead of diameters d = 0.6, 1, 2, 3, 4, and 5 mm, respectively. These individual wavelet responses are further rescaled at an equivalent unique diameter d = 1 mm and for a corresponding frequency range 100 kHz $\leq f \leq$ 5 MHz (Figure 3). We emphasize that the reference wavelet response is associated to a perfect half-space reflector.

2.2. Identification of the Coherent Frequency Bands

[12] Thanks to the controlled shape of the source signals used in the wavelet response method, the distortions observed in the wavelet response of the granular media when compared with the reference wavelet response of a perfect reflector (Figures 3a and 1b, respectively) may safely be attributed to wave phenomena produced by the heterogeneous nature of the glass bead layer. Both wavelet responses have a similar appearance at low frequency, and discrepancies are larger and larger when the frequency increases. The intermediate wavelength domain $\lambda \simeq \pi d$ marks a clear limit between the low-frequency domain where both wavelet responses look very similar with a common conical-like structure, and a high-frequency domain where the conical structure of the wavelet response becomes very complex in the case of glass beads.

[13] A quantitative analysis of the wavelet response may be done from its so-called ridge functions as detailed by *Le Gonidec et al.* [2002, 2003]. The analyzing wavelet used in the present study counts five extrema (Figure 1a) from which five ridge functions may be defined. Each ridge function is locked on a given extrema and may be followed across the dilation range spanned by the whole wavelet family. The average amplitude of the wavelet response along a given ridge function may be plotted in a log-log diagram as a function of the λ/d ratio as shown in Figure 3b. This average curve represents the reflectivity

2.2.1. Long-Wavelength Domain

[16] The long- avelength domains I– II correspond to reduced avelengths l > p*d* here the avelet response of the granular medium has a simple conical appearance identical to the reference avelet response ith 5 ridge functions (Figures 3a and 1b, respectivel). In these domains, the ave reflected b the surface of the granular medium appears as a single ave packet, identical to hat happens for an Heaviside-like discontinuit . The distinction bet een domains I and II is motivated b the slope break observed in the ridge functions at l = 2*d*p.

[17] In domain I, the ridge function is flat ith a = 0 indicating that the reflectivit does not depend on the frequenc of the incident ave. The e perimental reflection coefficient $R = 0.34$ is identical to the one predicted for an homogeneous half-space interface as sho n in section 5.1 [*Le Duff et al.*, 2002].

[18] The reflectivit observed in domain II is frequenc - dependent indicating that the granular medium can be assimilated to a homogeneous half-space ith frequenc - dependent properties. The reflectivit linearl decreases from $R = 0.34$ to $R = 0.15$ as the avelength shortens (in a log-log plot). The frequenc attenuation for glass beads $d = 1$ mm is then estimated to 0.02 dB/kHz. In section 3, e give ph sical interpretation of this decrease due to scattering processes hich get stronger as the reduced avelengths l /*d* shortens.

2.2.2. Intermediate-Wavelength Domain

[19] Domain III covers the range pd > l > pd/2 here the simple cone-like appearance of the avelet response prog- ressivel disappears and splits into subconical structures at l $\simeq$ 2*d* (Figure 3a). Observed from Figure 3b, the ampli- tude of the ridge functions does not obe a po er la and the reflectivit curve presents a deep minimum $R \simeq 0.025$ at l $\simeq$ 2*d*. The temporal limit plotted in black dots in Figure 3a does not coincide ith the time of the reference avelet response: e observe reflected ave trains longer in time than the reference avelets. Strong interactions occur inside the granular medium bet een the acoustic ave and the glass beads. We associate domain III to the transition region here the glass bead la er cannot be assimilated to a Heaviside-like interface but appears to be a comple structure.

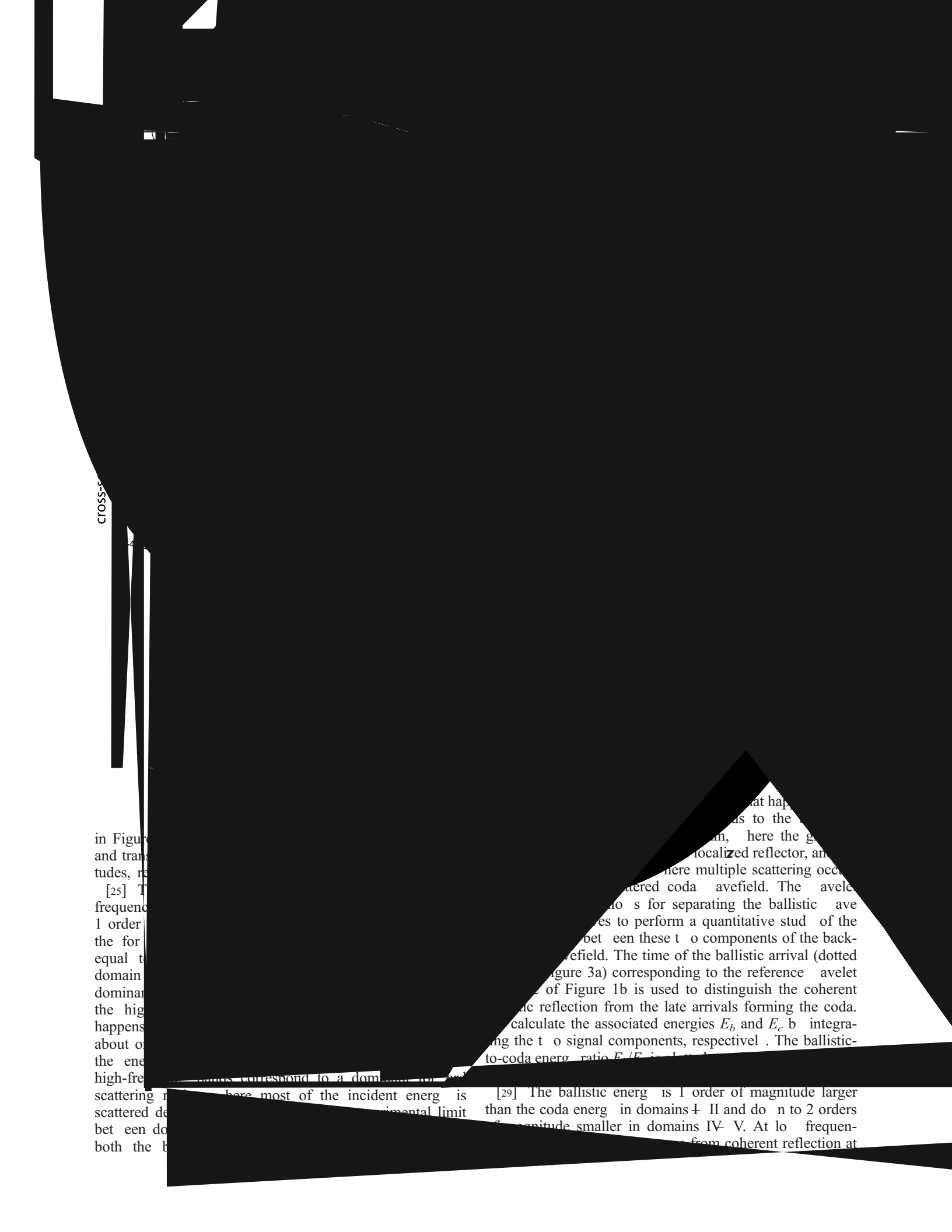
2.2.3. Short-Wavelength Domain

[20] Domains IV– V correspond to the avelength range l < pd/2 here the reflected ave trains have a total duration much longer than the one of the reference avelets. The reflected aves are mainl composed of a late coda t pical of strong multiple scattering bet een the source signals and the small-scale structures of the granular medium. A strong decrease of the ridge functions is observed in domain IV ith a slope a = +2 for pd/2 > l >2 d/p here the frequenc attenuation is 0.04 dB/kHz for glass beads $d = 1$ mm. In domain V, the slope of the ridge function is roughl a $\simeq$ 0 hen $r < 2$/p here the e perimental data scatted around a mean reflectivit $R \simeq 0.01$.

3. Wave Phenomena

3.1. Definition of Scattering Parameters

[21] The amplitude *f* of an acoustic plane ave 7(scatted)]TJET1.0996TLBT10.00260010.002650.7960862.36174Tm[(b)-394.4(an)-3



the interface, whereas it is mainly associated to multiple scattering at high frequencies where the scattered waves follow long tortuous paths in the heterogeneous medium.

[30] In frequency band I, the extinction coefficient follows a Rayleigh scattering law $\propto \lambda^{-4}$ [*Ishimaru*, 1978] (Figure 5b) indicating a single-scattering regime inside the granular medium when $\lambda > 2\pi d$ where propagation dominates. In domain II, transverse scattering increases for a single bead (Figure 4c), and the single-scattering regime is less and less valid. Domains IV–V correspond to multiple-scattering regime.

[31] At intermediate frequencies of domain III, the energies of the ballistic component and the coda are equivalent when $\lambda = 2d$, corresponding to a strong transition of a propagation regime at low frequencies to a diffusion regime at high frequencies. These experimental results on mean-field measurements (solid line in Figure 5a) are similar to the theoretical curve of the back-to-forward scattering energy ratio computed for a single glass bead (dotted line in Figure 5a) which microscopic coherence induces the macroscopic behavior of the granular medium.

4. Effective Medium Theories

4.1. Single-Scattering Regime

[32] We now consider effective medium models and consider their efficiency to reproduce the experimental reflectivity curve discussed in sections 2 and 3. A first class of models concerns the quasi-static models whose effective medium properties do not depend on the frequency. This is for instance the case of the models proposed by *Kuster and Toksöz* [1974] and by *Berryman* [1980] in the context of geophysical applications. These models are fully constrained by the experimental physical and geometrical properties of the granular medium, namely the shape, size, concentration and nature of both the inclusions (i.e., glass beads) and the fluid matrix (i.e., water). The models of *Kuster and Toksöz* [1974] and of *Berryman* [1980] are both derived by considering the statistical properties of a large number of elastic spherical inclusions randomly dispersed in a fluid matrix. The diffusing spheres of diameter d occupy a volume fraction f and their scattered far field is computed for signal wavelengths $\lambda \gg d$ using the single-scattering approximation. The physical properties of the equivalent homogeneous medium are the effective density, ρ^*, and the effective compressibility modulus K^*.

[33] In the model of *Kuster and Toksöz* [1974], the cluster of spheres embedded in the fluid matrix is replaced by a homogeneous equivalent sphere such that the scattered far field is unchanged in the fluid matrix. With this constraint, the effective density ρ^*_{KT} of the effective medium is a real-valued quantity given by

$$\frac{\rho_m - \rho^*_{KT}}{\rho_m + 2\rho^*_{KT}} = f\,\frac{\rho_m - \rho_s}{\rho_m + 2\rho_s}, \tag{6}$$

here ρ_s and ρ_m are the densities of the spherical inclusions and the fluid matrix, respectively. The concentration of elastic inclusions in the fluid matrix is $0.74 > f \geq 0$. The effective compressibility modulus K^*_{KT} is defined by Wood's law:

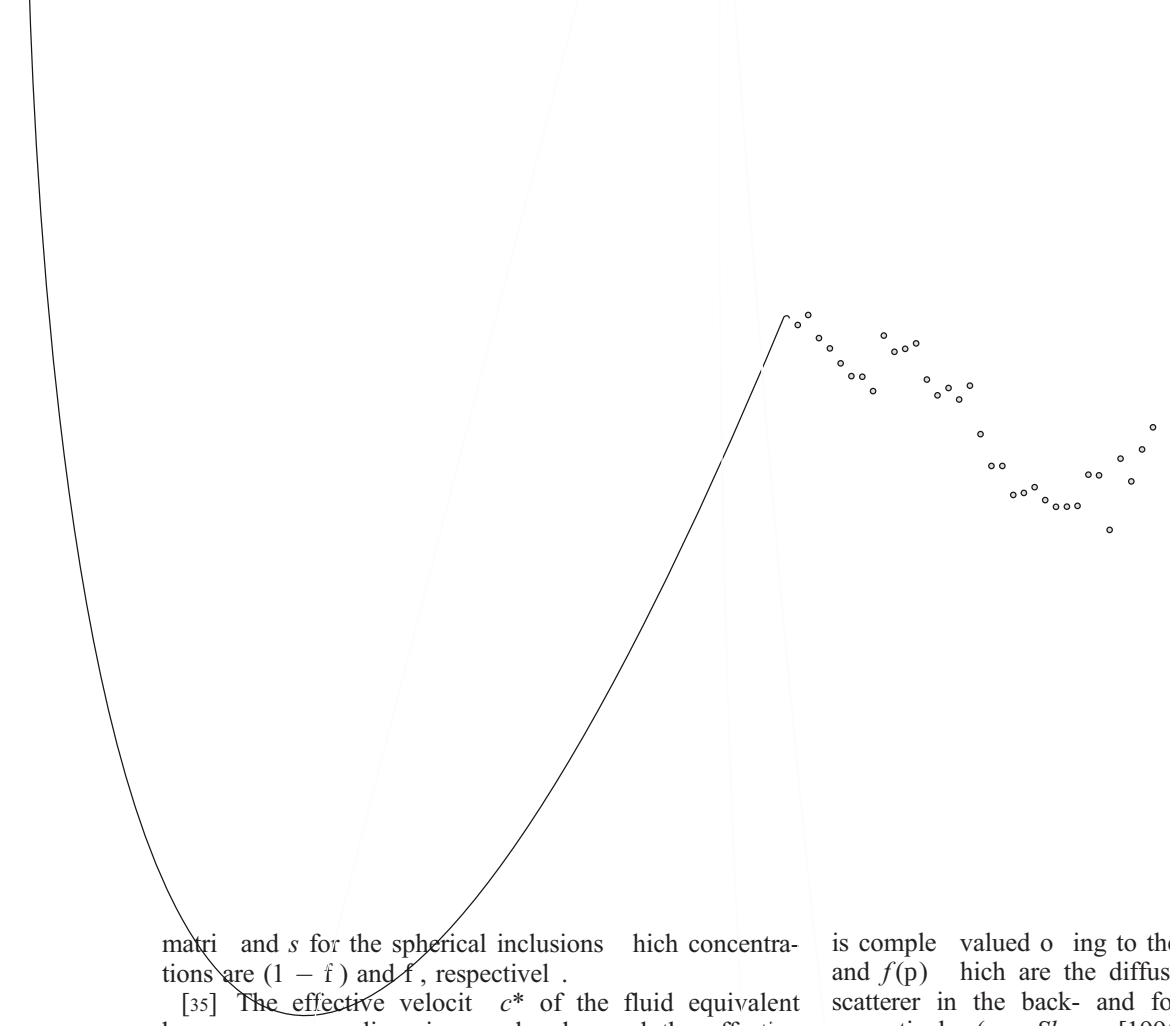
$$\frac{1}{K^*} = \frac{f}{K_s} + \frac{1-f}{K_m}, \tag{7}$$

here K_s and K_m are the compressibility moduli of the spherical inclusions and the fluid matrix, respectively.

[34] In the model of *Berryman* [1980], the same cluster of spherical inclusions in material s embedded in a fluid matrix m is replaced by a compound of inclusions in a homogeneous equivalent matrix * such that no scattered field is radiated outside the cluster of inclusions in material i and m, respectively, embedded in the effective medium *. Under this constraint, the effective density ρ^*_B is a real-valued parameter defined by

$$\frac{1}{\rho^*_B + \frac{1}{2}\rho^*_B} = \frac{f}{\rho_s + \frac{1}{2}\rho^*_B} + \frac{1-f}{\rho_m + \frac{1}{2}\rho^*_B}. \tag{8}$$

Note that formula (8) for the effective density is symmetric under interchange of constituent labels, m for the fluid



matri and s for the spherical inclusions hich concentrations are $(1 - f)$ and f, respectivel .

[35] The effective velocit c^* of the fluid equivalent homogeneous medium is a real value and the effective reflectivit g* follo s the real acoustic impedance contrast e pressed in equation (9):

$$c^* = \sqrt{K^*/\rho^*}, \qquad g^* = \frac{\rho^* c^* - \rho_m c_m}{\rho^* c^* + \rho_m c_m}, \tag{9}$$

here c_m = 1480 m/s and ρ_m = 1000 kg/m^3 is the sound velocit and densit of ater, respectivel .

4.2. Multiple-Scattering Regime

[36] *Waterman and Truell* [1961] have proposed an effective medium theor taking multiple scattering into account. This model has been applied to the problem of an elastic ave scattered b a finite number of inclusions inside a homogeneous matri [*McClements and Povey*, 1989; *Anson and Chivers*, 1993; *Robert et al.*, 2004]. This model also considers the case of spherical scatterers embedded in a fluid matri . The model is full constrained b the ph sical parameters of the e perimental granular medium. The properties of the effective equivalent medium are frequenc -dependent, and the model of *Waterman and Truell* [1961] belongs to the so-called class of d namic effective models.

[37] From a granular medium made of spherical inclusions, *Waterman and Truell* [1961] define an equivalent homogeneous medium hose effective properties are characterized b comple value parameters, the imaginar part of hich stands for scattering absorption. The effective medium ave number k^*, e pressed b

$$\left(\frac{k^*}{k_m}\right)^2 = \left(1 + \frac{2\pi n f(0)}{k_m^2}\right)^2 - \left(\frac{2\pi n f(\pi)}{k_m^2}\right)^2, \tag{10}$$

is comple valued o ing to the scattering parameters $f(0)$ and $f(\pi)$ hich are the diffusion amplitudes of a single scatterer in the back- and for ard scattering direction, respectivel (see *Sheng* [1995] for details). The ave number k_m is the (real) ave number in the fluid matri and $n = 6f/\pi d^3$ is the number of elastic spherical inclusions per volume unit. The inclusions are supposed to be uniforml distributed.

[38] From equation (10), the effective velocit of the equivalent fluid medium is also a comple -valued quantit and is e pressed in equation (11) corresponding to the effective medium immersed in ater (c_m and k_m are the sound velocit and the ave number in the ater, respectivel). The effective reflectivit g* follo ing the acoustic impedance contrast is given b equation (11) (the reflection coefficient of the glass bead la er is defined as the modulus of the effective reflectivit):

$$c^* = c_m \frac{k_m}{k^*}, \qquad |g^*| = \left|\frac{\rho^* c^* - \rho_m c_m}{\rho^* c^* + \rho_m c_m}\right|. \tag{11}$$

5. Comparison With the Experimental Data and Discussions

5.1. Very Long Wavelength Domain

[39] Identified from the e perimental avelet response, domain 1 is characterized b five ridge functions hich slope is $a = 0$ in a log-log diagram for avelengths $\lambda > 2\pi d$ (Figure 3b). In this frequenc band, the interface bet een ater and the la er of glass beads can be represented b a sharp Heaviside-like interface bet een ater and an equivalent homogeneous medium ith frequenc -independent properties. The reflected field is measured in the far-field condition and the e tinction coefficient curve plotted in

I II and IV V, the effective velocit $|c^*|$ is larger and smaller, respectivel , than the sound velocit in the fluid matri $c_m = 1480\ m/s$ and $|c^*| = c_m$ hen $l/d = 2$ in

[51] In the higher-frequenc domains IV and V, e sho a dominant for ard scattering for a single scatterer in accordance ith multiple-scattering phenomena observed ith the e istence of coda ave in the avelet response.

[52] From the avelet response e periments e perform in highl concentrated granular media, e observe scattering phenomena and quantif the results from theoretical approach based on effective medium methods. We stud in details the influence of the ratio l/d on the granular medium reflectivit curve. This ork, here e associate e perimental and theoretical results, can help in the understanding of acoustic probing of geological interfaces.

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