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ULTRASONIC WAVES IN SATURATED POROUS MATERIALS. DISCUSSION OF MODELING AND EXPERIMENTAL RESULTS

Mariusz Kaczmarek[1]

Jan Kochański

Józef Kubik[1]

Department of Environmental Mechanics, Pedagogical University in Bydgoszcz
e-mail: kubik@rose.man.poznan.pl

Models and experimental results obtained for ultrasonic waves in saturated porous materials are analyzed in order to assess the capability of the models to describe basic features of attenuation and dispersion of the waves. The physical mechanisms taken into account are: macroscopic relative motion of phases, micro-inhomogeneity of pore fluid velocity, intergranular friction, and micro-scattering. The role of macroscopic relative motion is studied basing on the results for dry and saturated materials as well as by comparison between wave characteristics for different parameters describing viscous and inertial interaction of the phases. The influence of micro-inhomogeneity of pore fluid velocity is tested throughout the history dependence of interaction force. The theoretical results that incorporate the intergranular friction resulting in complex bulk modulus of dry skeleton are compared with the experimental results for loose and sintered material. The porous samples are filled with water and tested by using the pulse transmission method and immersion technique. The experimental data for wide frequency range are processed derived by using of spectral analysis. The comparison of theoretical and experimental results shows good qualitative agreement between the predictions and experimental data.

Key words: saturated porous materials, ultrasonic waves, attenuation

[1]Until January 1, 1997, Department of Mechanics and Acoustics of Porous Media, Institute of Fundamental Technological Research of Polish Academy of Sciences, Poznań

1. Introduction

Sustained growth of interest in theoretical and experimental studies widespread in our environment porous materials has been observed. Among the phenomena, which particularly draw the attention of researchers dealing with porous materials are the problems of wave propagation in partially or fully saturated materials. The importance of such problems stems from practical needs for the predictive models of natural processes (e.g. propagation of seismic waves), is stimulated by human activity in the field of exploration of natural resources (e.g. petroleum prospecting) or is related to control, engineering or design of materials (e.g. nondestructive concrete testing, ultrasonography, investigation into new composite materials). As a consequence the field of theoretical or experimental studies of dynamics of porous materials is investigated by e.g. physicists, geophysicists, civil and biomedical engineers who use the phenomena related to the wave propagation as a tool to study soils, rocks, biological tissues, and other natural or man-made porous materials.

Specific features of dynamical behavior of the saturated porous materials result from the two-phase nature of the media. Particularly important are the effects related to the distribution of stress between solid and fluid phases, interaction between the phases (the latter one depending on instantenous intensity of macroscopic relative motion of the phases, and microscopic realization of fluid flow in pores and cracks), friction between grains, and scattering of waves from the fluid-solid and solid-solid interfaces. Due to the above phenomena attenuation and dispersion of waves in porous materials are stronger and, in general, more frequency dependent when compared to single phase materials. As a result the models appropriate for the latter cases have limited applicability to porous materials and when modeling of dynamics of saturated porous materials one should use two- or multi-phase theories. Like theoretical considerations also experimental investigations of porous materials must be based on specific methods to account for relatively strong attenuation and dispersion of the waves. These methods should provide the signals which have enough high energy to be detected after transmission through the materials.

The two-phase approach to modeling of dynamical behavior of saturated porqus materials was initiated by Kosten and Zwikker, Frenkel, and Gassmann and the mature model was developed by Biot (1957), (1962). Although further refinements of Biot's model including additional effects accompanying the wave propagation related to, e.g., lack of saturation, micro-inhomogeneity of fluid motion, and scattering of waves, were made by other researchers, e.g. Gardner, Geertsma, Stoll, Berryman, and Johnson, the so called Biot poroelasticity remains a fundamental model used as a starting point to theoretical studies and is useful in a number of areas of application of the model to porous materials. The salient feature of Biot's poroelasticity as compared with the model for single phase materials is the possibility of prediction of three kinds of bulk or volumetric waves (modes) in a saturated porous medium. Two of them are longitudinal waves and the last one is a shear wave. Moreover, it is worth noticing that one of the longitudinal waves (usually called the second or slow wave) is strongly attenuated and exhibits strong dispersion in comparison with the other waves. Recently developed models of saturated porous materials take into account the influence on attenuation and dispersion of waves of some other mechanisms not included within the original Biot theory, such as effects of squirt flow or scattering due to micro-inhomogeneities. As a result the theories cover a wide range of frequencies (from seismic to ultrasonic) and refer to a broad class of porous materials (from rocks to gels). Nevertheless, since the solid skeleton is usually assumed to be elastic or visco-elastic all the above mentioned models are more appropriate for description of dynamical behavior of rock-like materials than for soils.

The first works focused on experimental investigation of wave propagation in saturated porous materials were primarily performed as field studies and were connected with geophysical explorations. However, considerable progress in methodology and understanding of the phenomena related to the two-phase nature of such materials has been made in laboratories, where the second longitudinal wave predicted by Biot's model of poroelasticity was discovered by Plona (1980) and where other important results determining the properties of the three wave modes were obtained, see e.g. Johnson (1986), Jungman et al. (1989), Winkler and Plona (1982), Rasolofosaon (1988).

The aim of this paper is to discuss the mechanisms of attenuation and dispersion of mechanical waves in saturated porous materials from the viewpoint of modeling and experimental studies of waves within the ultrasonic range of frequencies.

The scope of the present contribution is limited to the effects incorporated within the linear macroscopic description including intrinsic sources of attenuation and dispersion. In such an approach the dissipative processes which convert mechanical energy into heat and scattering due to microscopic inhomogeneities are incorporated as opposed to the apparent effects caused by scattering due to macroscopic inhomogeneities or spreading of wave beams. The reported experiments are performed on dry or water saturated materials made of sintered and loose glass beads.

2. Experimental technique

Experimental investigations devoted to ultrasonic waves in porous materials are usually conducted by using the pulse echo or pulse transmission methods. In the reported studies the pulse transmission method combined with the immersion technique, similar to that used by Plona (1980) is applied, see Fig.1. The wave transducers are wide band with the center frequency of 1, and 2.25 MHz. The transmitting transducer is excited through a pulser by the electric pulse of 350 V of 4 μs duration. The receiving transducer is connected to the Link Instruments digital storage oscilloscope (DSO) attached to a personal computer (PC). To sample the data the oscilloscope is triggered by a synchronization signal generated by the pulser, which coincides with the probe excitation pulse. Any portion of the time record received by the DSO, sampled at a frequency up to 100 MHz, and digitized can be sent to the fast Fourier transform (FFT). The FFT algorithm provides the real and imaginary components of transformed signals which are used to calculate the amplitude and phase spectra. The measurements with the samples perpendicular and oblique with respect to the direction of wave beam were made. Calibration for the case of oblique samples is performed to adjust the position of the receiving transducer in the center of beam of the transmitted waves.

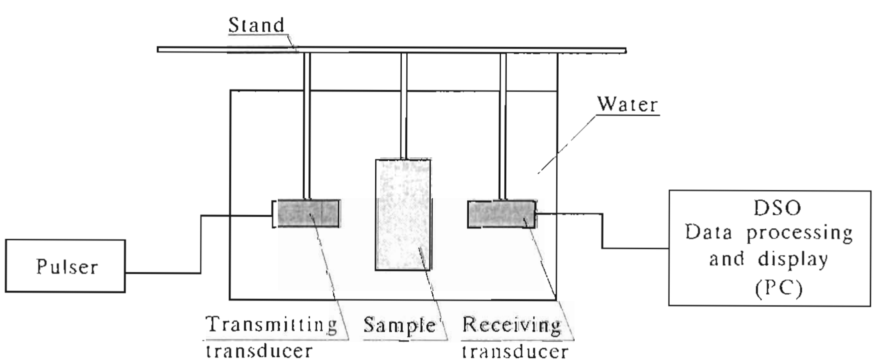

Fig. 1. Scheme of experimental setup for the applied immersion technique

In order to determine attenuation and phase velocity the tests for samples of the same material but different thicknesses (L_1, L_2) are made assuming that the energy of reflected waves at the boundaries in both cases are the same. In such a case the amplitude decay of the signal can be attributed solely to the increase in thickness of the samples. The frequency dependent attenuation coefficient α, and the phase velocity v, in this case are defined as follows

$$\begin{aligned} \alpha(f) &= \frac{1}{L_2 - L_1} \ln \frac{A_1(f)}{A_2(f)} \\ v(f) &= \frac{1}{L_2 - L_1} \frac{1}{2\pi n + \arctan \frac{I_2(f)}{R_2(f)} - \arctan \frac{I_1(f)}{R_1(f)}} \end{aligned} \tag{2.1}$$

where f is the angular frequency, $A(f)$, $R(f)$ and $I(f)$ are the amplitude, real and imaginary components of Fourier transform of the measured signals passing through the thinner (1) and the thicker (2) samples, respectively. An integer parameter n denotes the number of wavelengths, for a given frequency, which are contained in the distance $L_2 - L_1$. Its values must be chosen in the way ensuring that a reasonable value of the phase velocity for the considered range of frequencies is obtained from the Eq $(2.1)_2$.

The reported measurements are performed on samples of porous glass made of sintered or loose fractionated glass beads with the average grain diameters of 80, 140, and 275 μm. The overal time preparing the sintered sample including heating and cooling of samples was equal to about 13 hours while the sintering performed at a constant temperature between 650 and 680°C (adjusted to the grain size of a sample), lasted about three hours.

In order to test the accuracy of the experimental setup the attenuation and phase velocity were determined for water using the same procedure as for the studied porous materials. Maximum deviations of the attenuation coefficient and phase velocity from the exact values equal 0.001 Neper/mm for the attenuation, and 1% for the phase velocity were assumed as the accuracy of the measurement technique.

3. Modeling

The approach to modeling of dynamical behavior of saturated porous materials which takes into account the presence and interaction between fluid and solid phases due to their relative motion is based on the assumption of two overlapping continua. Following the methods of continuum mechanics the continua are described by independent sets of coupled balance equations and constitutive functions with additional terms corresponding to the interaction between phases. In the linear case such a model for saturated porous materials was first developed by Biot (1956) who used energetic methods to derive two coupled balances of linear momentum including the information on stress-strain response of the material and interaction force between the phases. An alternative approach to the equations derivation is the formalism of multiphase media theory using balances of linear momentum combined with constitutive relationships which define surface forces and interaction between the phases, see e.g. Bowen (1984).

Hereinafter, the elements of the linear model of wave propagation in saturated porous material are reviewed and most important physical mechanisms causing attenuation and dispersion of ultrasonic waves are discussed.

3.1. Mathematical modeling of wave propagation

The linear model of wave propagation in saturated porous materials written in terms of the displacement of solid skeleton $\boldsymbol{u}$ and displacement of fluid $\boldsymbol{U}$, may be based on the two following equations see e.g. Biot (1956), (1962), Johnson (1984), (1994), Stoll (1990)

$$
\begin{aligned}
\rho^s(1-f_v)\frac{\partial^2 \boldsymbol{u}}{\partial t^2} &= P\nabla(\nabla\cdot\boldsymbol{u}) + Q\nabla(\nabla\cdot\boldsymbol{U}) - N\nabla\times\nabla\boldsymbol{u} + \\
&\quad + b\Big(\frac{\partial \boldsymbol{U}}{\partial t} - \frac{\partial \boldsymbol{u}}{\partial t}\Big) - \rho_{12}\Big(\frac{\partial^2 \boldsymbol{U}}{\partial t^2} - \frac{\partial^2 \boldsymbol{u}}{\partial t^2}\Big) \\
\rho^f f_v\frac{\partial^2 \boldsymbol{U}}{\partial t^2} &= R\nabla(\nabla\cdot\boldsymbol{U}) + Q\nabla(\nabla\cdot\boldsymbol{u}) - b\Big(\frac{\partial \boldsymbol{U}}{\partial t} - \frac{\partial \boldsymbol{u}}{\partial t}\Big) + \rho_{12}\Big(\frac{\partial^2 \boldsymbol{U}}{\partial t^2} - \frac{\partial^2 \boldsymbol{u}}{\partial t^2}\Big)
\end{aligned}
\tag{3.1}
$$

The parameters N, P, R and Q are in general complex value functions of frequency that refer to elastic and/or frictional properties of solid skeleton and fluid. In a particular case, for purely elastic phases, the parameters can be expressed by the bulk modulus of fluid K_f, bulk modulus of solid material K_s, bulk modulus of porous skeleton K_b, shear modulus of the skeleton N, and porosity f_v, see e.g. Biot and Willis (1957). Parameters ρ_f and ρ_s stand for mass densities of fluid and solid material, and ρ_{12} denotes the coefficient which expresses inertial force (inertial drag or added mass force) between the fluid and skeleton. The coefficient b determines viscous interaction between the phases (viscous drag). Both coefficients that define interaction between phases: ρ_{12} and b are in a general case of harmonic waves functions of frequency and the latter effect define the history dependent drag force between the fluid phase and solid skeleton. The history dependence of non-stationary interaction force expresses the dependence of the instantaneous macroscopic interaction on microscopic realization of pore fluid velocity. One should notice that the currant distribution of microscopic fluid velocity is determined by such factors as the macroscopic rate of the fluid flow, pore structure, fluid viscosity, and in the case the non-stationary flow is influenced by propagation of the shear waves due to viscosity at the pore level (the waves propagate from the internal surface of skeleton towards the pore center). If one neglects the history dependence of interaction force, the parameters ρ_{12} and b can be approximated by the values which correspond to the flow of ideal fluid (ideal fluid approximation) and a viscous flow at a constant velocity (quasi-static approximation), respectively (see Kaczmarek and Kubik, 1988). In this case

$$\rho_{12} = f_v \rho^f (1 - \alpha_T) \qquad b = \frac{f_v^2 \mu}{k} \tag{3.2}$$

where the structural parameters α_T and k are defined as the tortuosity and permeability of porous material, respectively, and μ denotes the viscosity of fluid. Some researchers formulate Eqs (3.1) in such a way that one of the parameters b or ρ_{12} is a complex value function of frequency while the other vanishes or remains a constant, see Biot (1956), Johnson et al. (1994). Then, the history of viscous and inertial interaction between the phases is combined in a single term and its physical meaning corresponds to the general concept of impedance. The latter type of formulation is equivalent to the proposed above where ρ_{12} and b are real value functions of frequency. In order to determine particular forms of the frequency dependent parameters b and ρ_{12} different models of fluid flow in pores are considered. For example, the model of straight circular or flat channels with the axes parallel to the direction of macroscopic flow was exploited by Biot (1956) to introduce frequency correction for high frequency range of the coefficient of viscous interaction. The two models formulated for virtual components of saturated porous materials using the results for a non-stationary flow in circular channels and a flow around spheres within wide frequency range were proposed by Kaczmarek and Kubik (1988). A network of straight channels with randomly distributed radii was considered by Johnson et al. (1987) to determine the frequency dependent coefficients of viscous and inertial drags.

By using standard methods of wave analysis, see e. g. Biot (1956), Eqs (3.1) can be used to derive the dispersion relations for all the bulk waves in porous media. The dispersion relation describing the two longitudinal waves has the form

$$\begin{aligned} &Yl^4 + \Big\{Hbif - \Big[\rho^s(1-f_v)R + \rho^f f_v(2N+A) - H\rho_{12}\Big]f^2\Big\}l^2 + \\ &+\Big[\rho^f\rho^s f_v(1-f_v) + \rho_{12}\rho\Big]f^4 - \rho bif^3 = 0 \end{aligned} \tag{3.3}$$

where l is the complex wave number, f denotes the angular frequency and

$$Y = (2N+A)R-Q^2 \qquad H = 2N+A+R+2Q \qquad \rho = (1-f_v)\rho^s + f_v\rho^f$$

The dispersion relation for the shear wave reads

$$N\Big[bif - (f_v\rho^f - \rho_{12})f^2\Big]k^2 + \Big[\rho^s(1-f_v)f_v - \rho\rho_{12}\Big]f^4 - \rho bif^3 = 0 \tag{3.4}$$

where k denotes the complex wave number of the shear wave.

The solutions to the dispersion equations (3.3) and (3.4) with respect to l and k give information on frequency dependence of the phase velocities v_i and attenuation coefficients α_i, of the two longitudinal waves $(i = 1,2)$ and the shear wave $(i = s)$, respectively, propagating in saturated porous materials. The equations can be also used in theoretical studying the influence of particular physical parameters and corresponding mechanisms on dispersion and attenuation of waves.

Both attenuation and dispersion of waves in porous media are in general frequency dependent and related by the Kramers-Kroning relation resulting from causality condition. The condition formulates the fact that the response of material to a driving force cannot precede the arrival disturbance generated by this force. The Kronig-Kramers relation can be written as follows, Xu and King (1990)

$$\frac{f}{v(f)} - \frac{f}{v_\infty} = H[\alpha(f)] \tag{3.5}$$

where H denotes the operator of Hilbert transform and v_∞ stands for the highest value of phase velocity.

3.2. Mechanisms causing attenuation and dispersion

3.2.1. Thermal relaxation

As a result of the phenomenon of thermomechanical coupling propagation of mechanical waves through materials (including porous materials) induces small local changes in temperature. Becouse of the effect of heat conduction the temperature variations diffuse into vicinities of the places where local changes in temperature appear. These processes lead to the irreversible loss of mechanical energy and attenuation of waves, Bourbie et al. (1987).

3.2.2. Intracrystalline dumping, intracrack and intergranular friction

Among the mechanisms of wave attenuation that are related only to the phenomena which occur in a material of the solid skeleton are intracrystalline dumping, and friction between surfaces of cracks and grains. The former dissipation mechanism is associated with such effects as dislocations, glide and climb, Budiansky and O'Connell (1980). In turn, the Coulomb friction between grains and/or internal crack surfaces of porous material in response to the wave propagation results directly in dissipation of mechanical energy producing heat. The friction mechanism is of a primary importance for energy dissipation in dry granular materials within lower frequency range. Although the presence of wetting liquid on grain boundaries reduces friction, this mechanism may also significantly contribute to energy dissipation in saturated rocks, Johnston and Toksoz (1979), Tittmann et al. (1984). The characteristic feature of the attenuation due to frictional dissipation expressed by a quality factor is the frequency independence of the latter one.

3.2.3. Macroscopic relative motion of fluid and skeleton

Wave propagation through saturated porous and permeable media induces macroscopic (or alternatively called overall, global or coherent) motion of a fluid relative to a skeleton from the regions of bulk compression to the regions of its bulk dilatation. This global relative motion of the phases is responsible for the essential part of the total dissipation of energy due to viscous loss in a pore fluid, Biot (1956), (1962). Since this energy loss is determined by the viscous *drag force between fluid and solid, the attenuation and dispersion of waves* in the materials is influenced by the two structural parameters which define the macroscopic viscous interaction force: porosity and permeability of porous material, as well as is influenced by the viscosity of fluid. Due to significant differences in permeability of porous materials the overall flow mechanism is the primary factor determining attenuation in water saturated coarse granular materials (sand) over wide frequency range, but may have a negligible influence on the attenuation in fine materials (silt or clay) unless waves of very high frequency are considered.

3.2.4. Local inhomogeneity of fluid flow (micro-motion of fluid)

While the global relative motion of a fluid with respect to a skeleton takes place during wave propagation through permeable materials, an instantaneous microscopic or local forms (realizations) of the fluid flow at a pore level can be influenced by the internal structure of porous material (size and shape of grains and channels, smoothness of internal surface, presence of fractures, etc.) and the process of wave propagation. The attenuation and dispersion of mechanical waves in porous materials is determined not only by macroscopically measurable relative motion of the phases (as described above) but also by detailed microscopic realization of the fluid velocity. Among the mechanisms that are considered to exerte a strong influence on the microscopic realization of the flow are the following effects: intercrack squirt flow (Mavko and Nur, 1979), intracrack flow, and micro-shear waves related to fluid viscosity, (Kubik and Kaczmarek, 1988). The liquid squirt and intercrack flow involve a fluid flow between cracks and a flow of intergranular fluid due to compression and dilation of cracks or grain contacts, Mavko and Nur (1975), O'Connell and Budiansky (1977). The micro-shear waves accompany the nonstationary bulk flow of fluid in pores. The latter waves propagate from internal boundaries of the skeleton and cause the history dependence of the macroscopic interaction force between phases.

3.2.5. Micro-scattering

Scattering due to inhomogeneities at the interface between the solid and pore fluid and/or between solid grains constituting the skeleton is an important mechanism causing attenuation and dispersion of waves in porous materials when the higher frequency range is considered. If the wavelength is much longer than characteristic sizes of grains or pores the role of scattering can be modeled by the weak scattering theory (or the model of Rayleigh scattering). Although the models of porous materials which include the Rayleigh scattering are constructed mostly for dry porous materials, see e.g. Sayers (1981), they also predict the experimentally observed negative velocity dispersion of fast ultrasonic waves and proportionality of attenuation to the fourth power of frequency in saturated materials, Jungman et al. (1989).

3.2.6. Macroscopic inhomogeneities

The presence of large-scale inhomogeneities of mechanical or structural properties of porous materials with a characteristic scale much larger than the wavelength may cause scattering at the macro-level and the corresponding attenuation and dispersion of waves or when the inhomogeneities are smooth enough to disregard reflections of waves from the inhomogeneities they cause the attenuation of waves without any contribution to the wave dispersion (see Chaban, 1993). Using the geometrical acoustics approximation the latter mechanism of attenuation of waves can be attributed to the interaction of rays arriving at any point of the medium with different phases. It was shown that the attenuation caused by this mechanism is frequency dependent in a linear way.

3.3. Results and discussion

In Section 3 the linear isotropic model of wave propagation in saturated porous materials is discussed with a particular attention focused on physical mechanisms that influence attenuation and dispersion of mechanical waves. In order to analyze the influence of these mechanisms on wave parameters theoretical results will be obtained for the ultrasonic frequency range taking as the starting point the set of material constants determined for a sintered porous glass (the material is called Ridgefield Sandstone, see Johnson et al. 1994) saturated with water (the numerical values of material parameters for Ridgefield Sandstone are given in Appendix).

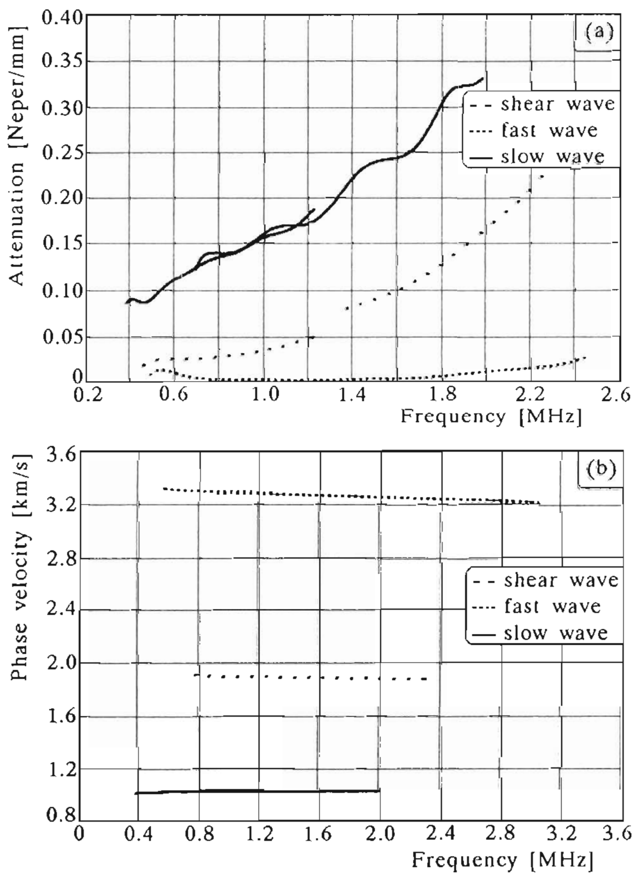

Fig. 2. Experimentally determined attenuation (a) and phase velocity (b) for water saturated sintered glass beads

These results are compared with the experimental result obtained for the porous glass made in the laboratory of the Department of Environmental Mechanics at Pedagogical University in Bydgoszcz. The comparison has a qualitative character not aiming at verification of the model which will be the subject of another paper.

According to the prediction of the two-phase model there are two longitudinal and one shear wave propagating in saturated porous materials. All these waves can be observed within the ultrasonic frequency range. In Fig.2 the experimentally determined attenuation coefficients and phase velocities for water saturated sintered glass are shown. The results were obtained for the samples made of sintered glass beads with the average grain diameter equal to $80\,\mu m$.

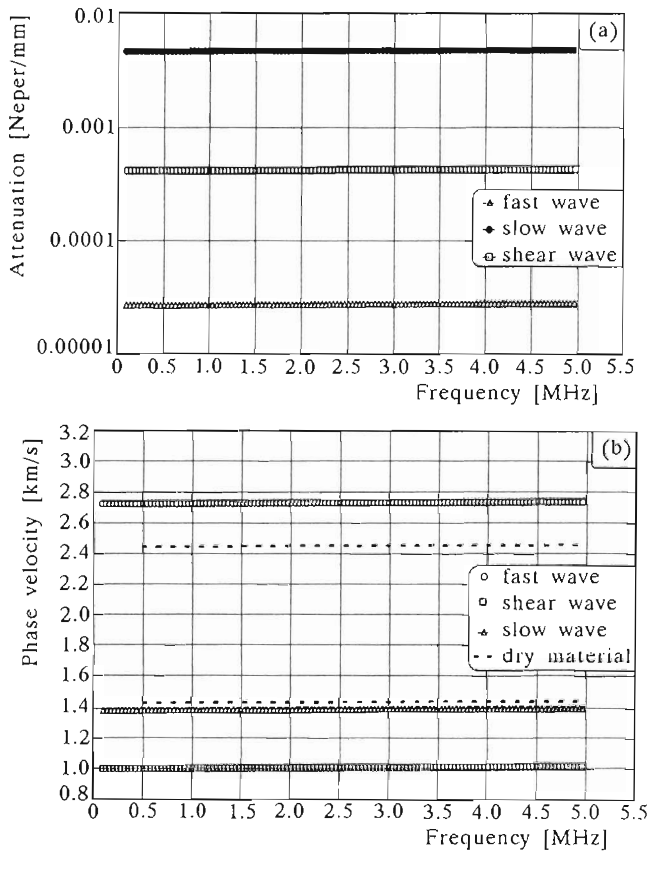

Fig. 3. Theoretical predictions of attenuation (a) and phase velocity (b) for Ridgefield Sandstone

The experimental results confirm the existence of the three bulk waves in saturated porous materials and show substantial differences in values of the velocities and attenuation coefficients of the detected waves. A rough qualitative agreement between the experimental results and model predictions is seen from the comparison of the experimental results from Fig.2 with the theoretical data given in Fig.3. The theoretical results are obtained assuming that attenuation and dispersion of waves depend only on instantaneous relative macroscopic motion of the phases (elastic moduli and parameters characterizing viscous and inertial interactions of solid and fluid are real and constant coefficients).

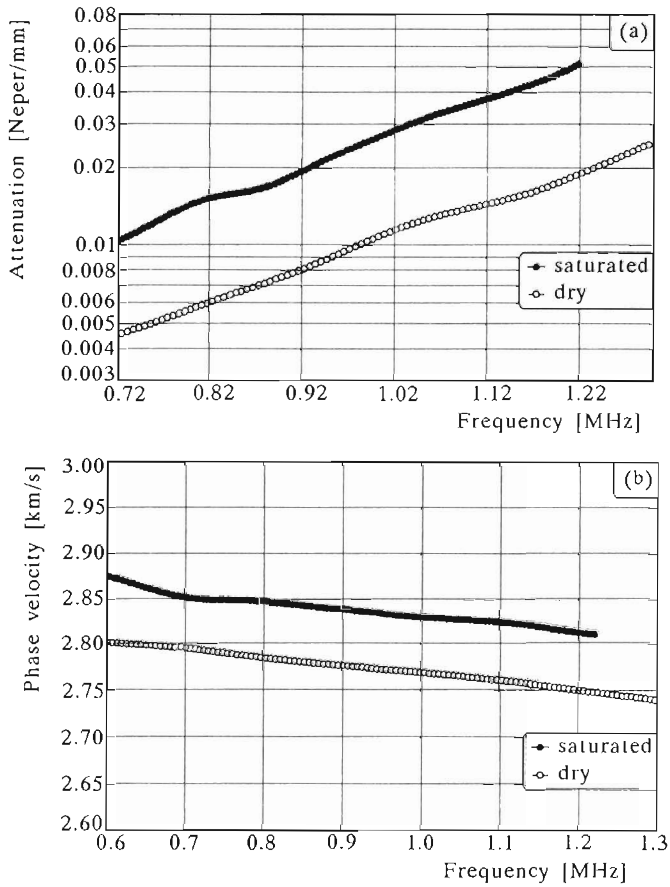

Fig. 4. Comparison of experimentally determined attenuation (a) and phase velocity (b) of the fast wave for dry and saturated materials

In order to highlight the role of pore fluid in wave propagation in a saturated material in Fig.3, additionally, the values of velocities of longitudinal and shear waves were depicted. One should notice that within the considered model there is no attenuation and dispersion of the waves in a dry porous material. The experimental results that confirm the importance of saturation of porous materials are shown in Fig.4, where the wave parameters for dry and saturated materials are compared. The compared data are obtained for a longitudinal wave in a dry material and a fast wave in water saturated sintered glass made of grains with the average diameter equal to 140 μm. The negative dispersion of phase velocity and the way of dependence of attenuation coefficient on frequency (see the following discussion) indicate that scattering effects are visible. Additionally, one can notice that contrary to the model prediction the experimentally determined attenuation in a dry porous material is not negligible.

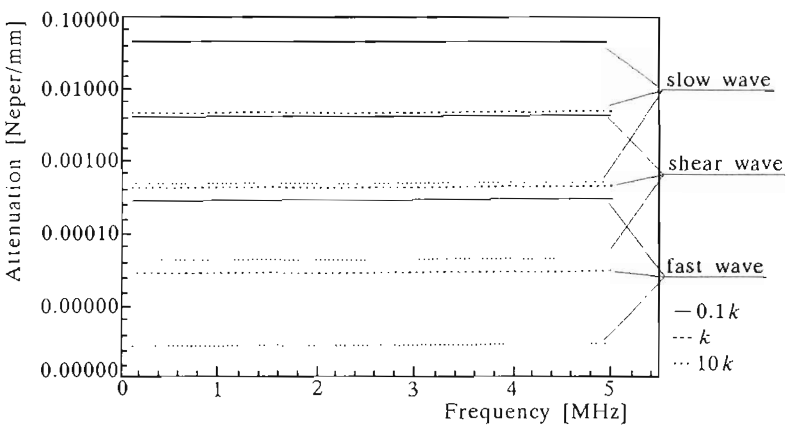

Fig. 5. Study of the influence of permeability variation on attenuation of fast, slow and shear waves

Taking into account the fact that the role of relative motion of phases in dynamics of saturated porous materials depends strongly on structural parameters of material; permeability and tortuosity which determine viscous and inertial drag forces between the phases Fig.5 and Fig.6 illustrate the influence of these parameters on attenuation coefficients and wave velocities. Since the model does assume that the relative motion of the phases is the only source of dissipation of energy the permeability exerts a tremendous influence on waves attenuation. The model does not show a strong influence of permeability on ultrasonic wave velocities.

The influence of tortuosity α_T, on the theoretically predicted velocity and attenuation of the two longitudinal waves in a saturated material is plotted in Fig.6 assuming that the tortuosity is equals 1 (no inertial drag), 1.58 (the value

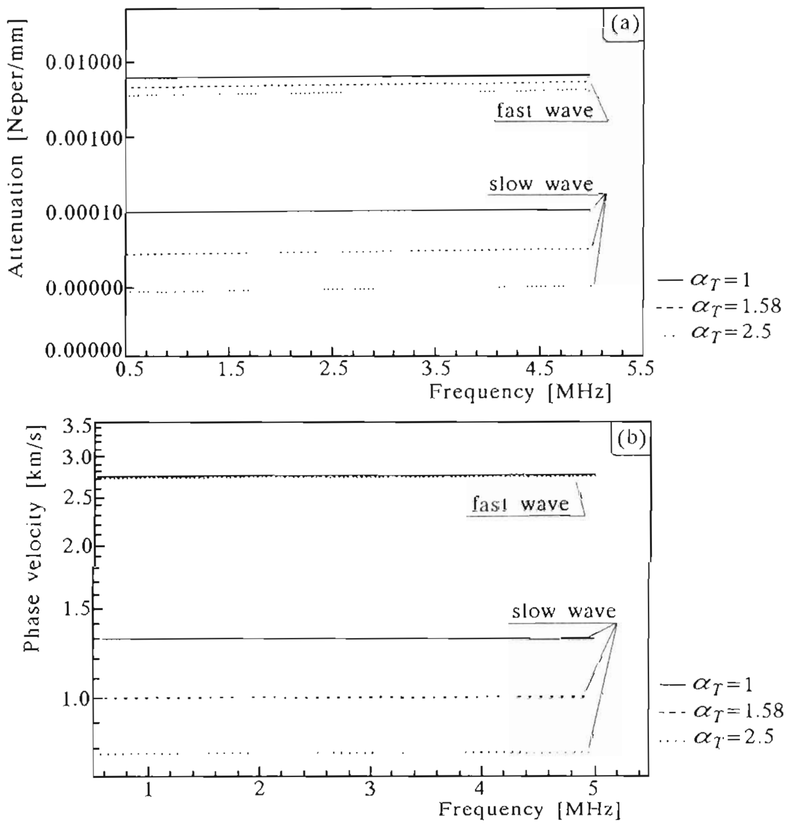

Fig. 6. Study of the influence of tortuosity on attenuation (a) and phase velocity (b) of fast and slow waves

really determined for Ridgefield Sandstone), and 2.5, respectively. The results show minor sensitivity of the fast wave velocity to changes of tortuosity and a relatively big influence of the parameter on the other wave characteristics.

Although all the above theoretical results have been obtained for the two-phase model of saturated materials in which it is assumed the quasistatic approximation for viscous drag and ideal fluid approximation for inertial drag it is well proved (mainly based on microscopic considerations) that the interaction between phases is history dependent. In order to compare the former model with the model which includes the dependence of interaction forces on frequency (the history dependent model) in Fig.7 the results for the model of randomly distributed channels elaborated by Johnson et al. (1994) are compared with the model which ignores frequency dependence of parameters

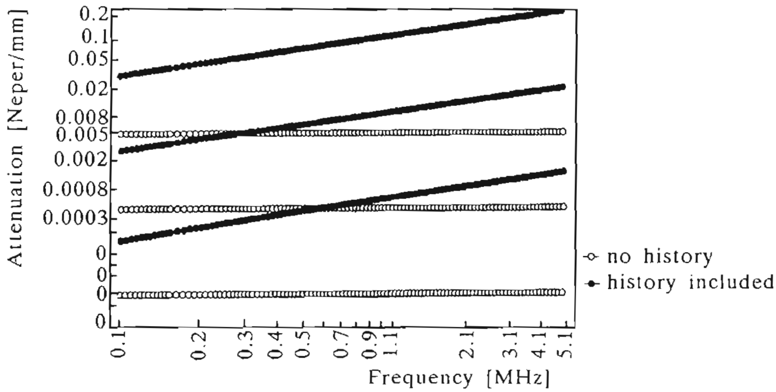

Fig. 7. Attenuation of the three bulk waves predicted by models with and without history dependence

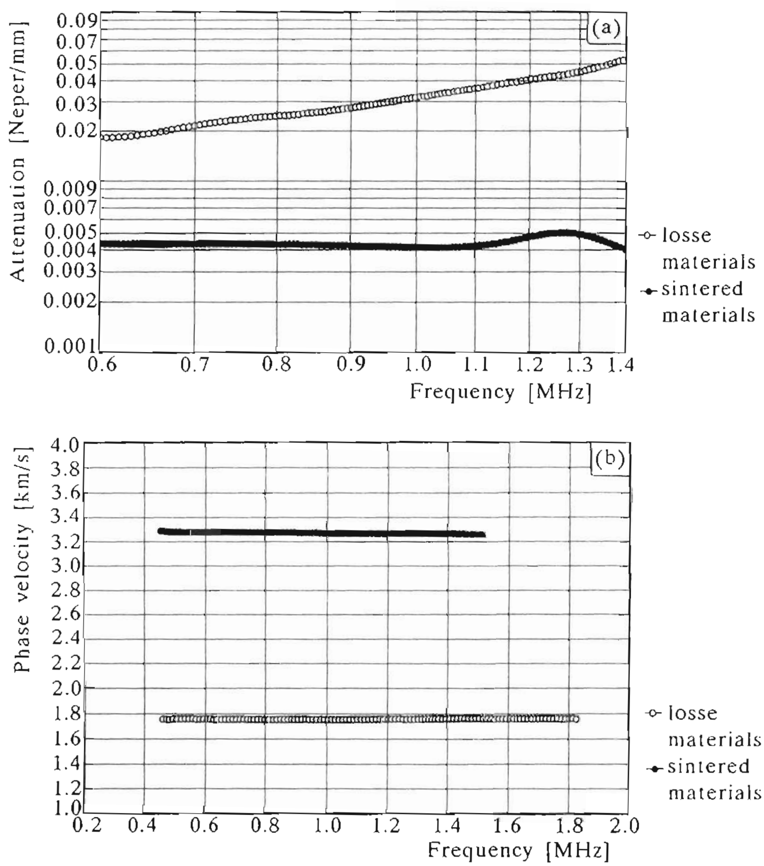

Fig. 8. Comparison of attenuation (a) and phase velocity (b) of the fast wave for loose and sintered materials

contributing to interaction force. Within the ultrasonic frequency range the model which incorporates the history dependence of interaction force has no effect on the wave velocities (the results are not shown) but may strongly influence the attenuation of the waves. It can be seen from Fig.7 that the history dependence has similar influence on all the waves. Due to intrinsic and complex nature of the effect the role of history dependence on wave characteristics cannot be easily verified experimentally.

In order to assess the role of internal friction between grains of solid skeleton the experimental results which pertain to the fast wave propagating in loose and sintered glass saturated with water are compared in Fig.8. The results were obtained for the material with the average grain diameter equal to 80 μm. Since both porosity and permeability of the sintered and loose materials are comparable the results indicate a substantial role of friction for both attenuation and velocity of the fast ultrasonic waves.

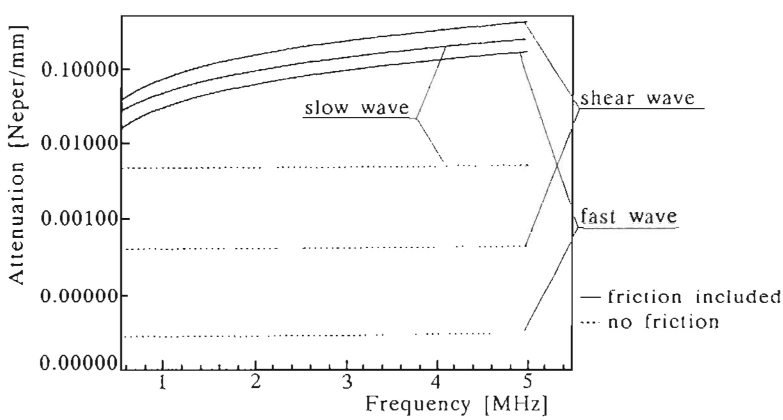

Fig. 9. Model predictions for attenuation of fast, slow, and shear waves for complex (friction included) and real (no friction) bulk moduli

For comparison, the role of internal friction modeled by complex elastic moduli of solid skeleton (see Stoll, 1990) is analyzed in Fig.9. The figures show the attenuation of all the bulk waves for the model with complex elastic moduli and include the predictions of the model with real bulk modulus. Following by Holland and Brunson (1988) the ratio between imaginary and real parts of the complex bulk modulus of the skeleton are assumed to be equal to 1/30. While the velocities of waves are not influenced by the complex modulus (the results are not shown) the attenuation coefficients may depend on the friction parameters.

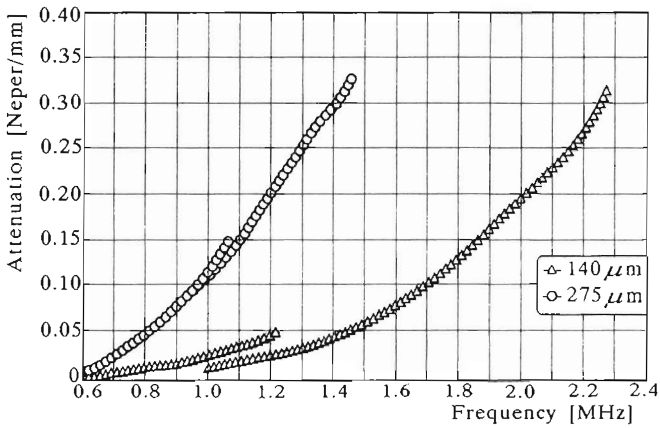

Fig. 10. Experimental results for attenuation in the Rayleigh frequency domain

The last of the analyzed factors which determines propagation of ultrasonic waves in porous media is the scattering of waves due to microinhomogeneities constituted by grains or pores of the materials. The experimental results showing the role of scattering in attenuation of the fast wave are given in Fig.10 (the influence of scattering was also evident in Fig.4). The results exhibit the dependence of attenuation coefficient on a log-log plot on frequency to the power 3.8. Such a frequency dependence is typical for the Rayleigh scattering domain for which the wavelengths are much longer than the microinhomogeneities (scatterers). Additionally, the importance of scattering results from the shift of lower limit of strong dependence of attenuation on frequency for the material with larger grains to lower frequencies (longer waves). Theoretical considerations for dry porous materials show that the model with the frequency dependent complex bulk modulus can describe the influence of scattering on attenuation and dispersion of waves within the Rayleigh domain, see Sayers (1981). However, since such a model assumes that scatterers are isolated and there is no relative motion of phases the model cannot be directly applied to saturated permeable materials.

4. Conclusions

The theoretical predictions which take into account different mechanisms of attenuation and velocity dispersion of waves in saturated porous materials are analyzed and compared with experimental data for the ultrasonic frequency range. The comparison shows a good qualitative agreement for the effects of saturation, history dependence, and intergranular friction. There is not enough experimental evidence to separate the influence of history dependent interaction force on wave parameters from the other physical mechanisms. Although there exists a good qualitative agreement of the experimental results for attenuation due to the Rayleigh scattering with the model constructed for materials with isolated pores further effort is needed to include the role of connectivity of pores and the resultant permeability of the materials. It is worth noticing that since the wave parameters of saturated porous materials are strongly influenced by a few physical mechanisms and the influences cannot be easily separated further verification of macroscopic models of wave propagation in the materials is required and specific for these types of materials experimental action correlated with careful theoretical considerations is necessary.

A. Appendix

Table 1. Material parameters for Ridgefield Sandstone, Johnson et al. (1994)

Parameter	Value
Porosity f_v	0.36
Permeability k	$27.7 \times 10^{-12}\,\mathrm{m}^2$
Tortusosity α_T	1.58
Fluid viscosity μ	$1.0 \times 10^{-3}\,\mathrm{kg/ms}$
Fluid density ρ^f	$1.0 \times 10^{3}\,\mathrm{kg/m}^3$
Solid density ρ^s	$2.48 \times 10^{3}\,\mathrm{kg/m}^3$
Bulk modulus of pore fluid K_f	$2.25 \times 10^{-9}\,\mathrm{N/m}^2$
Bulk modulus of solid material K_s	$49.9 \times 10^{-9}\,\mathrm{N/m}^2$
Bulk modulus of skeleton frame K_b	$5.24 \times 10^{-9}\,\mathrm{N/m}^2$
Shear modulus of skeleton frame N	$3.26 \times 10^{-9}\,\mathrm{N/m}^2$

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Fale ultradźwiękowe w nasyconych materiałach porowatych. Modelowanie a wyniki eksperymentalne

Streszczenie

W pracy przeanalizowano wyniki teoretycznych i eksperymentalnych badań dotyczących propagacji fal ultradźwiękowych w nasyconych materiałach porowatych celem oceny efektywności modelowania podstawowych cech tłumienia i dyspersji prędkości fal. Mechanizmy fizyczne, które zostały wzięte pod uwagę są następujące: makroskopowy względny ruch faz, mikro-niejednorodność pola prędkości cieczy, tarcie pomiędzy ziarnami i mikroskopowe rozpraszanie na niejednorodnościach. Rolę makroskopowego ruchu względnego faz zbadano na podstawie porównania wyników dla suchego i nasyconego materiału oraz dla modelu z różnymi wartościami parametrów struktury. Znaczenie niejednorodności pola prędkości cieczy porowej przeanalizowano w ramach modelu z siłą oddziaływania zależną od historii względnego ruchu faz. Przewidywania teoretyczne uwzględniające tarcie pomiędzy ziarnami, wyrażone przez zespolone moduły sprężystości, zostały porównane z wynikami eksperymentalnymi dla luźnych i spiekanych materiałów. Porowate próbki szklane nasycone wodą badano techniką impulsową w zanurzeniu. Dane eksperymentalne uzyskano stosując analizę spektralną w szerokim zakresie częstotliwości. Przeprowadzona analiza pokazuje dobrą jakościową zgodność przewidywań teoretycznych oraz danych doświadczalnych.

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