NONLINEAR ACOUSTIC EFFECTS IN ROCKS AND SOILS

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INTRODUCTION

When natural materials are loaded by a stress field, dramatic changes in modulus occur as the microstructure deforms, even if there is no permanent macroscopic damage. The effect is primarily due to pervasive, thin microfractures which easily close under load. The pressure derivative of a generalized elastic modulus, M=dC/dP, for most intact solids equals ~5, but can be two orders of magnitude higher for rocks and soils [1]. Nonlinear terms in the stress strain relation that governs material response can therefore be very important. Measurements of longitudinal and shear velocity under hydrostatic and uniaxial loading for various rocks are reported to illustrate these phenomena. Observations of amplitude dependent attenuation are presented to show direct evidence of nonlinear behavior. New results presented here for partially saturated rocks show the strongest nonlinear response yet reported.

The formalism of nonlinear elasticity were developed to describe the consequences of lattice anharmonicity, which implies material imperfection on the atomic scale [2]. We will use this same formalism as a framework to quantify effects that result from the larger scale material defects which dominate the material response of rocks at low pressure.

PRESSURE AND STRESS DEPENDENCE

A linear increase of the sound velocity with hydrostatic pressure indicates that the infinitesimal theory of elasticity is no longer applicable. Measurements with sufficient precision to verify this behavior were made many years ago for metals [3] and cubic crystals [4]. Larger, and hence more easily detected pressure effects were observed for rocks [1]. Ultrasonic measurements for Nugget sandstone, a fine grained rock with high crack density, illustrate how important these effects can be. Longitudinal and shear velocities were measured with a contact pulse transmission technique in a fluid pressure medium, and are plotted in Fig. 1. The pressure derivative of the bulk modulus, dK/dP, computed from the linear fit of Fig. 1, is $\sim 4.4\times10^3$. The correlation coefficient for the regression is 0.97, indicating that the deviation from linear elasticity is mainly second order. The effect of higher order terms becomes evident at higher pressures. The dK/dP is two orders of magnitude higher at 40 MPa than at 900 MPa, at which point thin, compliant cracks are closed by pressure [5].

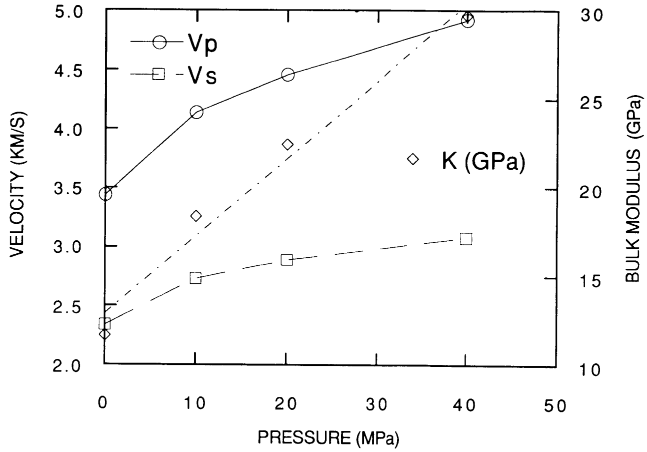

Fig. 1. Longitudinal and shear velocities and bulk modulus for Nugget sandstone as a function of pressure. The linear fit shows the strong pressure dependence of the modulus.

Even stronger deviations from linear elasticity occur in low stress uniaxial loading experiments when the internal porosity is partially filled with water. New experimental results for a volcanic rock from southern Nevada, Butte lapilli tuff, demonstrate this higher stress sensitivity, as shown in Fig. 2. The travel time of 1 MHz longitudinal waves was measured perpendicular to the loading direction, so that travel time decreases with load. Extensive signal averaging was used to obtain the time resolution necessary for these measurements [6]. The two data sets are for two slightly different saturations, suggesting that the stress sensitivity is strongly dependent on water content. For stresses of up to 0.02 MPa, velocity changes are two orders of magnitude more sensitive to changes in load than is typical for experiments at higher stress (eg. Fig. 1). These results are the first of this type and the role of pore shape, mineralogy and fluid composition have yet to be investigated.

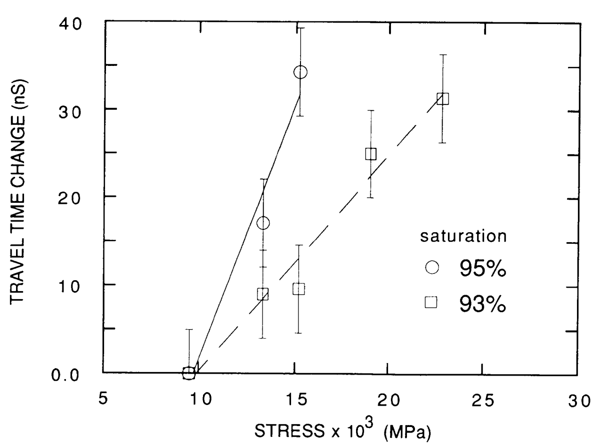

Fig. 2. Increase in longitudinal travel time as a function of uniaxial stress for Butte lapilli tuff. A small prestress is applied before changes are recorded to ensure uniform loading.

AMPLITUDE DEPENDENCE OF ATTENUATION

Amplitude dependent attenuation has been observed both at low [7] and ultrasonic frequencies [8], although most results, including those discussed here, are audio and low frequency 'internal friction' measurements. For most attenuation data, a linear fit of the form

$$Q^{-1} = Q_0^{-1} + \gamma\varepsilon \quad (1)$$

where Q_0 is a weakly frequency dependent term, ε is the strain, and γ is the strain sensitivity, is sufficient to describe the observed behavior. A data summary for the amplitude dependent component of attenuation from the literature for sands and clays [9,10] salt [11], sandstone [12] and granite [13], is plotted in Fig. 3. In Fig. 3, the slope of the data, γ, is a convenient measure of the nonlinear component of the attenuation for a particular material. The solid symbols are new data for granite, before and after the sample has been

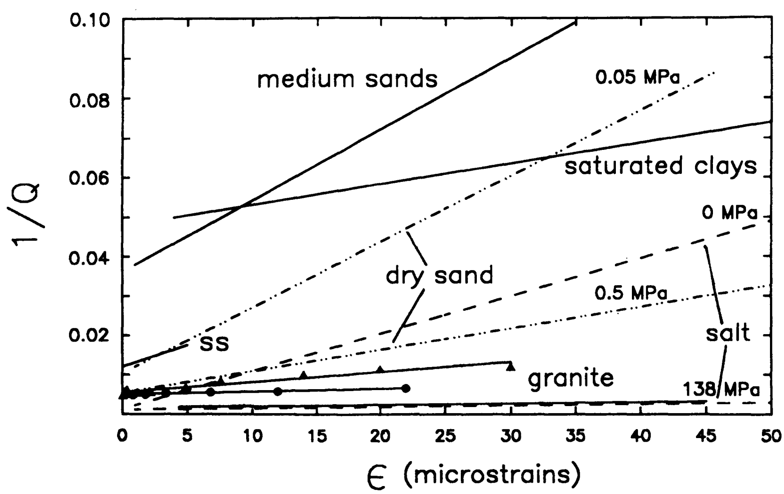

Fig. 3. The nonlinear component of attenuation for a wide variety of earth materials. The effect of confining pressure is shown for unconsolidated sand and salt.

damaged by fatigue in torsion [14]. Average strains never exceeded 3×10^{-4} during cycling. An increase in γ by about a factor of four after cycling illustrates the sensitivity of γ to microstructure, in this case an increase in crack density. Some of the data reported here from the literature may also be biased by fatigue effects. Confining pressure decreases γ by closing grain boundary microcracks which are the primary contributors to the nonlinear effect. For example, unconsolidated sands rapidly lose strain sensitivity when confined. Pressures of 0.5 MPa are sufficient for γ to reach values typical for competent sandstone.

NONLINEAR BEAM MIXING

When nonlinear terms are taken into account in the wave equation, the selection rules predict the existence of a difference beam which arises from an interaction region where two input beams intersect. The effect is well known, particularly in underwater acoustics, but had not been observed until recently in rocks. Beam mixing experiments in the 400 kHz region by Johnson, Shankland and colleagues [15] have demonstrated that collimated, low frequency beams can be produced in granite and sandstone by nonlinear wave interaction. Frequency, amplitude, and angular relationships predicted by theory for the output beam are corroborated by the experiments. A wavefield superposition experiment for Berea sandstone [16] is shown in Fig. 4. Wavetrains from each of two transmitting transducers (input beams) are detected and stored separately. Then the mixed wavefield, including the difference beam, is generated by exciting the input beams simultaneously (top trace). The input beams are then subtracted from the mixed wavefield to reveal the difference beam generated by the interaction of the two input beams. The resulting difference waveform (lower trace) arrives at the time appropriate for the mixed longitudinal and shear mode path predicted by theory.

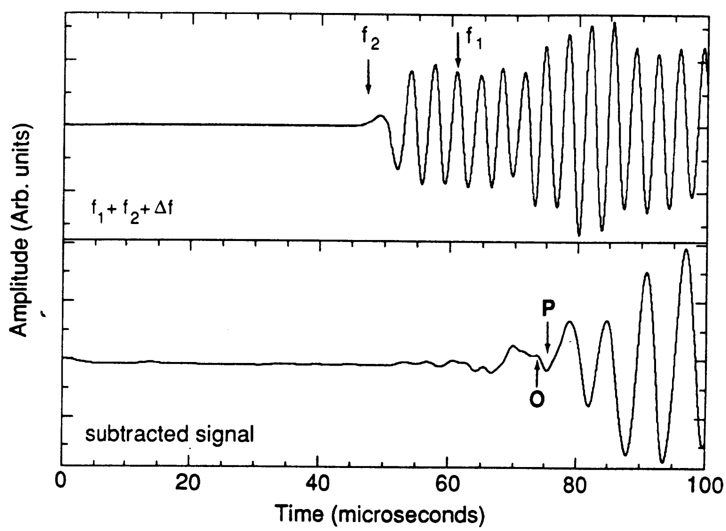

Fig. 4. Results of a beam mixing experiment for Berea sandstone. Input beams are denoted by f1 and f2. Arrivals of the individual input beams are as indicated on the upper trace. The lower trace, amplified about 1000x, shows the predicted (P) and observed (O) arrival of the difference beam.

SUMMARY

Strong nonlinear effects are easily detected in rocks and soils when strains exceed a material dependent threshold, usually of the order of 10^{-6}. Pressure dependence of the modulus, amplitude dependent attenuation, and nonlinear beam mixing have all been documented as examples of nonlinearity. Similar effects should be observable in other materials susceptible to extensive microfracturing, such as structural ceramics. It may be possible to develop new NDE methods for such materials based on experience gained from natural materials.

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