A Typical Amplitude Effect on Seismic Wave Velocity and Attenuation in Consolidated Rocks Under Pressure (Rock Physics)

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Summary

A series of experiments were carried out to investigate the influence of strain amplitude on wave velocity and attenuation in samples of sandstone, dolomite and single quartz. The measurements were performed using ultrasonic pulse transmission technique and the reflection method (frequence of 1 MHz) on the strain amplitude ~10^{-6} under pressure from 1 to 60 MPa.

Introduction

The effect of strain amplitude on wave velocity and attenuation is known from earlier works [*Johnston, and Toksoz*, 1980; *Winkler et. al.*, 1979; *Johnson et. al.*, 1996; *Ten Cate et. al.*, 1996; *Van Den Abeele et. al.*, 1997; *Zinszner et. al.*, 1997; Tutuncu, 1998 *Ostrovsky et. al.*, 2001]. However the character of this dependence (sign of variation with amplitude) is considered exactly established and unchangeable. The wave velocity decreases with increasing amplitude, and in the same time the attenuation is increased. Now this rule is subjected to a doubt. Due to microplasticity the modulus can both decrease and increase with increasing strain [*Mashinskii*, 1994]. This problem is scantily explored. Theoretical work by *McCall and Guyer* [1994] showed that the elastic modulus both decreases and increases with strain due to the curvature in the stress-strain relation $\sigma(\varepsilon)$. The static experiments showed a multilevel character of $\sigma(\varepsilon)$, presenting an increase and a decrease of the modulus [*Mashinskii*, 2001]. There are another observation that contradict well-known experimental data. It is rare field measurement that showed an increase in with strain amplitude [*Mashinskii et al.*, 1999]. New results of the amplitude effects is presented below.

Method

The study nonlinearity of dolomites was performed using transmission technique with the uniaxial pressure [Mashinskii, 2004]. The apparatus includes acoustic transducers of P and S pulses (f_P = 750 kHz and f_S = 350 kHz). It is used two approach of the time measurement: a) the time from the start to the first arrival; b) The interval time from the start to the amplitude peak. The wave speed is measured on four amplitudes ($A_{1.0}$, < $A_{1.5}$, < $A_{2.1}$, < $A_{3.0}$). We are interested the relative accuracy which is important for our purpose. The calibration shows the accuracy of 0.2 percent for P wave and 0.4 percent for S wave.

Examples

It is established that the compressional velocity depends on strain amplitude, and the shear velocity does not depend on amplitude in the range (1-3)$\times 10^{-6}$ and pressure of 5-20 MPa. Determined by the first arrival time the compressional velocity increases with amplitude, however, if it is determined by the peak time, takes place the decrease in the velocity (Fig. 1). For the upward and downward pressure the curve V_p (P_{uniax}) exhibits an open hysteresis, yielding a residual component of velocity. An intersection of the branches of the hysteretic loop is observed in a more porous dolomite in comparison with a less porous dolomite. This intersection is most manifested in the residual components of the dynamic bulk modulus and Poisson's ratio. The unusual behavior of the wave velocity with amplitude is presumably explained by features of the rock inelasticity (at least microplasticity), which require the further researches.

The study nonlinearity of sandstone and single quartz was performed using the reflection method in three-layer model [Mashinskii, 2005]. The first and third layer is beryllic bronze. The rock sample is between these layers. The confining pressure on the sample is 20 MPa. The studying is conducted by the closed amplitude cycle. The amplitude discretely increases from the minimum to the maximum magnitude, and back: $A^{\varepsilon}_{\min} = A^{\varepsilon}_{1} \to A^{\varepsilon}_{2} \to \ldots \to A^{\varepsilon}_{\max} = A^{\varepsilon}_{6} \to A^{\varepsilon}_{1} = A^{\varepsilon}_{1}$

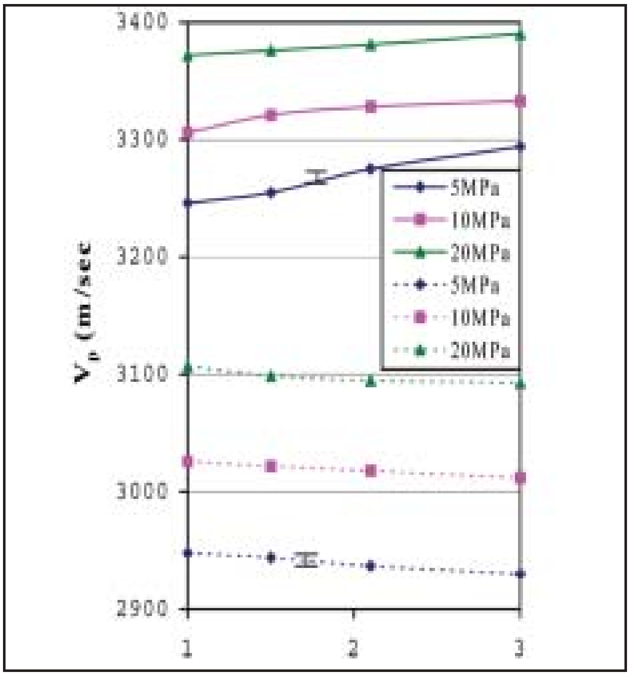

Fig. 1. Dependence of compressional velocity in dolomite with porosity K_p = 2.4% at pressure of 5-20 MPa on strain amplitude. Solid line shows the velocity, computed by the arrival time and dashed line shows the velocity, computed by the peak time. Representative error bars are shown.

Relative error of the wave velocity measurement can be estimated by the formula:

$$dV / V = dS / S + dt_{arrival} \ / \ t_{arrival}, \tag{1}$$

where $t_{arrival}$ – the propagation time of pulse in the sample, dS, and $dt_{arrival}$ - absolute error of measurement S and t, accordingly. The velocity divergence does not exceed 0.2%. In order to estimate relative accuracy many repeated measurements of wave velocity have been carried out on the constant amplitude. Great number of measurements shows that the deviation of the velocity value is not more than 0.2 %.

The propagation velocity for the first minimum and maximum (V^{min} and V^{max}) is calculated as follows:

$$V^{\min} = 2S / (t_{reflected-\max} - t_{source-\min}), \tag{2}$$

$$V^{\max} = 2S / (t_{reflected-\min} - t_{source-\max}), \tag{3}$$

where S - a sample's thickness; $t_{source-min}$ - the arrival time of the first minimum of the excitation pulse; $t_{source-max}$ - the arrival time of the first maximum of the excitation pulse; $t_{reflected-min}$ - the arrival time of the first minimum of the reflected pulse; $t_{reflected-max}$ - the arrival time of the first maximum of the reflected pulse. The attenuation was calculated by using the relation [*Winkler, 1983*]

$$Q^{-1} = \alpha V / 8.686 \pi f = \alpha \lambda / 8.686 \pi, \tag{4}$$

where α is the absorption coefficient in dB/m, V is the phase velocity in m/s, and f is the frequence in hertz.

The behaviour of V_p in sandstone in dependence on strain amplitude is ambiguous. A wave velocity V_p^{min} does not change with increasing amplitude. A velocity V_p^{max} slightly but confidently increases with amplitude. In view of the small variation in velocity (~ 0.7%) the latter result is regarded only as a tendency. The attenuation Q_p^{-1} in sandstone decreases with increasing strain amplitude (Fig. 2). This decrease achieves 16% when the amplitude increases from minimum to maximum in the ε_d range. The V_P and V_s in smoky quartz do not depend on strain amplitude, but and decrease with amplitude. The decrease in attenuation achieves 10% and 6.5%, accordingly in the all amplitude range. This result contradicts the existing concept. The unusual behavior of attenuation is presumably explained by feature of the rock inelasticity (at least by microplasticity) that requires the further research. The amplitude dependences can be used, as are supposed, as an additional criterion in a geological interpretation of seismic data.

We advance the some theory assumptions explaining the nonlinearity of velocity and attenuation. The amplitude dependence is caused by the variation of the inelastic contribution in strain, which consists of sum of an ideally elastic component and two inelastic components ($\varepsilon_i = \varepsilon_{i-e} + \varepsilon_{v-e} + \varepsilon_\mu$) . Instantaneous Young's modulus is given [*Mashinskii*, 2004]

$$E_i = \frac{\Delta\sigma_i}{\Delta\varepsilon_i} = \frac{\Delta\sigma_i}{\Delta\varepsilon_{i-e} + \Delta\varepsilon_{v-e}(t_\sigma) + \Delta\varepsilon_\mu(|\varepsilon|)}, \tag{5}$$

where $\Delta\varepsilon_{i-\varepsilon}$ is an ideally elastic component, $\Delta\varepsilon_{v-e}(t_\sigma)$ is the time-dependent viscoelastic component and $\Delta\varepsilon_\mu(|\varepsilon|)$ is the strain-dependent microplastic component. The change in modulus is caused by microplasticity. Usually $\Delta\varepsilon_{i-e}$, $\Delta\varepsilon_{v-e}(t_\sigma)$ components increase in proportion with increasing stress. It leads to the modulus decrease. However in some rocks there is the disproportionate change of the component. Then are possible both the decrease and the increase of strain increment with increasing stress. If the

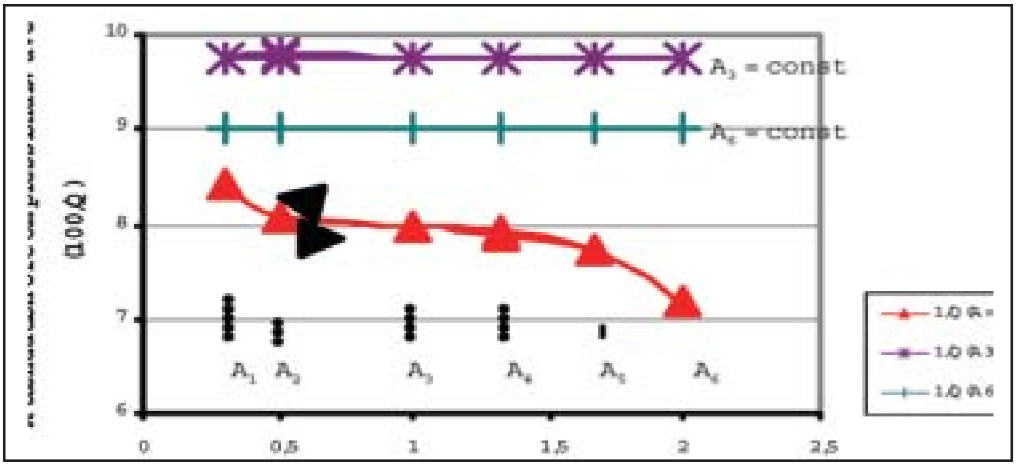

Fig. 2. Dependence Q_p^{-1} on strain amplitude in Nivagalsk sandstone at confining pressure 20 MPa. The strain amplitude changes upward and downward as the closed circle: $A^{\varepsilon}_{min} \rightarrow A^{\varepsilon}_{max} \rightarrow A^{\varepsilon}_{min}$ (see arrows). The measurements on two constant amplitudes and conducted in the same condition are combined with amplitude plot.

decrease of strain increment takes place then the decrease of the inelastic contribution occurs also. The decrease means the increase of in (5). This is in accordance to theory of *McCall and Guyer* [1994]. In rock having the positive curvature of σ(ε) the elastic modulus increases with increasing stress, and for the negative curvature of σ(ε) the elastic modulus decreases with increasing stress.

The classic viscoelastic mechanism does not suppose the decrease of viscoelastic component with increasing stress. However the decrease in is possible if the relaxation time will depend on the stress. Then the value will decrease and the modulus will increase with stress under condition that the increase in occurs as well. The rock can have the relaxation time spectrum that is given

$$T_{rel} = \sum_{i=1}^{n} T_{rel(i)} f(\sigma) \qquad (6)$$

The relaxation spectrum can include the set, which is presented by the relaxation times depending on the stress level. We suppose that can both decrease and increase in dependence on the stress level.

Conclusions

There is the faint influence of amplitude on velocity and, on the contrary, the strong reaction of attenuation on the amplitude variation. The change of the rock's rigidity on account of the amplitude increase in this strain range is small. Therefore the change of modulus (wave velocity) is insignificant also. Thus the elastic modulus is the less sensitive parameter to the amplitude variation. The same change of the rock's rigidity in the same amplitude range leads to the considerable change in attenuation. Therefore the attenuation parameter is more sensitive parameter. The nonlinear propagation of seismic waves in the wide amplitude range should be continued to fluid-saturated rocks.

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