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Effect of strain amplitude and confining pressure on the velocity and attenuation of *P* and *S* waves in dry and water-saturated sandstone: an experimental study

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Abstract
In rock physics, much attention has been paid to the study of the processes of strain of natural materials at small strains. Experiments using high-precision measurements have allowed new knowledge at micro/nano level to be acquired. The microplasticity of solids is studied in materials science, but there is also data regarding some rocks. The property of microplasticity of natural materials is still little studied. The study was carried out on rock samples. The effect of strain amplitude and confining pressure on the velocity and attenuation of *P* and *S* waves in dry and water-saturated sandstone has been studied. The method of reflected waves was used in the frequency range of 0.5–1.4 MHz at four strain amplitudes $(0.5–1.67)\cdot 10^{-6}$ Amplitude cycling causes an open and closed hysteresis effect for wave velocity and attenuation. This has been observed for both dry and water-saturated sandstone. The hysteresis loop overlaps in both states. The amplitude changes in the velocity of *P*-wave in dry sandstone is 1.12 %, and the attenuation of *P*-wave in dry sandstone is 5.43 %. As for *S*-wave, its maximum attenuation in dry sandstone reaches 8.81 %. The behavior of a wave velocity and attenuation can be explained by the combined effect of viscoelasticity and microplasticity. Elastoplastic transition strongly depends on the details of the microstructure, its defectiveness, and other parameters. The characteristics of the complications of wave parameters can be the signs of the internal structure of the subject.

Keywords
rock physics, amplitude-dependent wave velocity and attenuation, open hysteresis of wave velocity and attenuation, effect of water saturation on wave velocity and attenuation, microplastic strain, stepwise inelasticity, elastic modulus

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СВОЙСТВА ГОРНЫХ ПОРОД. ГЕОМЕХАНИКА И ГЕОФИЗИКА

Научная статья

Влияние амплитуды деформации и всестороннего давления на скорость и затухание *P*- и *S*-волн в сухом и водонасыщенном песчанике: экспериментальное исследование

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Аннотация
В физике горных пород большое внимание уделяется изучению процессов деформирования природных материалов на малых деформациях. Эксперименты проводятся с помощью высокоточных измерений, которые позволяют получить новые знания на микро/нано уровне. Микропластичность твердых тел изучают в материаловедении, но имеются также данные, полученные для некоторых гор-

ных пород. Свойство микро-пластичности природных материалов пока мало изучено. Исследование проводилось на образцах пород. Изучено влияние амплитуды деформации и всестороннего давления на скорость и затухание *P*- и *S*-волн в сухом и водонасыщенном песчанике. Использовался метод отраженных волн в диапазоне частот (0,5–1,4) МГц при четырех амплитудах деформации $(0{,}5–1{,}67)\cdot10^{-6}$. Циклическое изменение амплитуды вызывает эффект открытого и закрытого гистерезиса для скорости волны и затухания. Это наблюдается как для сухого, так и водонасыщенного состояния песчаника. В обоих состояниях имеет место перехлест петлей гистерезиса. Амплитудное изменение скорости *P*-волны в сухом песчанике составляет 1,12 %, а для затухания *P*-волны в сухом песчанике – 5,43 %. На *S*-волне максимальное затухание в сухом песчанике достигает 8,81 %. Поведение скорости и затухания волны можно объяснить совместным действием процессов вязко-упругости и микро-пластичности. Упругопластический переход сильно зависит от деталей микроструктуры, ее дефектности и других параметров. Характеристики осложнений параметров волн могут являться признаками внутреннего строения исследуемого объекта.

Ключевые слова

физика горных пород, амплитудно-зависимые скорость волны и затухание, открытый гистерезис скорости и затухания волны, влияние водонасыщения на скорость волны и затухание, микропластическая деформация, скачкообразная неупругость, упругий модуль

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Introduction and challenges

The current development of earth sciences is based on new fundamental knowledge in the physics of rock strain, in order to increase performance of seismic and acoustic methods in geological surveys and exploration. New knowledge has been obtained about the mechanism of natural material strain under various loads. These are inelastic step-like, discontinuous strains recorded at micro/nano level. The property of rock microplasticity, which is rather exotic in geophysics, can manifest itself even at small and very small strains. Accounting for this factor is important in practice, since seismic and acoustic methods use a range of small strains. The interest in this effect has emerged as a result of previous studies. The study of seismic non-linearity has led to the need for a deep understanding of the physics of rock strain [1–3]. The possibility of non-linearity at very small strains was confirmed, thus extending the applicability of inelastic processes [4, 5]. Theoretical studies in seismic improve the classical visco-elastic model of a standard body. The model well describes dispersion, relaxation, and related inelastic processes.

Theoretical and experimental studies confirm the presence of the microplasticity effect [6, 7]. The influence of strain amplitude on a wave velocity and attenuation is ambiguous, since in some cases it leads to an increase in the parameters, while in the others, to a decrease. In the same way, the modulus of elasticity changes, affecting the curvature of the stress-strain relationship [8, 9]. This non-standard behavior of rocks is caused by the joint effect of elastic and microplastic strain [10-11]. This effect is presented as a “stress plateau” and “stress drop” on a stress–strain diagram and in an acoustic response record [12, 13]. The property of microplasticity of rocks allows for irregular short-term “switching on” of the plasticity process with the simultaneous effect of elastic strain. There are also theoretical confirmations [14–16]. The mechanical properties of rocks differ to a greater extent in their inelastic characteristics. They are more related to the dynamic parameters of waves than to the elastic characteristics. The current approach involves the use of new data which can be used to resolve geological problems. This is confirmed by high-precision experimental and theoretical studies [17, 18].

Research in solid state physics has shown that a viscoelastic model can be supplemented with an inelastic element of a discontinuous nature, involved in the deformation process. An elastic-viscoplastic model with the participation of a plastic component represents an amplitude-frequency-dependent dynamic modulus. In this model, the general stress tensor is determined by the sum of three components, elastic, elastic-plastic, and viscoelastic moduli of a material [19–21]. In solid state physics and materials science, much attention is paid to the study of step-like strain [22–24]. There is a sharp transition from elastic strain to plastic flow. Such a strain jump is accompanied by a stress drop and depends in a complex way on the properties of a material and its loading conditions [25, 26]. The development of a mechanical model of a geological medium takes into account the data obtained on discontinuous inelasticity. Some data for rocks and minerals (sandstone, clay loam, quartz, silica, muscovite, stishovite, mica, sapphire, diorite, graphite) are described in [27, 28].

This paper describes a laboratory study of the effect of strain amplitude and pressure on the behavior of velocity and attenuation of *P*-wave and *S*-wave in dry and water-saturated sandstone at room temperature. This study is of great interest for understanding micro-strain mechanisms in rocks. The mechanism of microplasticity of rocks is still poorly understood, but it seems reasonable to say that it is close to a mechanism known in solid state physics. Microplastic behavior occurs when mobile dislocations are activated in the form of an avalanche phenomenon. The first sign of this process is the appearance of the “stress plateau” and “stress drop” effects. The results obtained in this experiment can be useful not only as a fundamental knowledge, but also for their application in solving practical problems. New knowledge about the microplasticity property of rocks allows the standard viscoelastic model used in seismic surveys to be improved. This can be achieved by including a microplastic strain component into the standard model. A complex viscoelastic-plastic model can more realistically describe strain processes in rocks. In the practical application of the knowledge acquired, for example, in seismic and acoustics, the amplitude-dependent effect that affects the velocity and attenuation of longitudinal and transverse waves in rocks needs to be taken into account. Accounting for this effect improves the measurement accuracy and the interpretation of the obtained data.

Research techniques and factual material

In the experiment, samples of fine-grained sandstone from a core taken from a depth of 2,545 m were used. The density of sandstone is 2.45 g/cm^3, the content of fine-grained sand fraction is 82 % and that of siltstone is 18 %, the total porosity is 12 %. The measurements of the velocity and attenuation of *P* and *S* waves depending on the strain amplitude were carried out at a constant hydrostatic pressure of 20 MPa. In addition, the behavior of *P* and *S* wave velocities at constant amplitude was studied depending on the hydrostatic pressure in the range from 10 to 50 MPa. The cylindrical specimens used had the following dimensions: 40 mm in diameter and 16 mm in length. A standard three-layer installation was used in the experiment [29, 30]. The first and third layers provided identical wave reflection at the interfaces. The first layer is the delay line and the third layer is the acoustic load. A rock sample is located between these layers. The excitation and reception of acoustic responses were provided by piezoceramic sensors at frequency of 1 MHz, which were set to polarize *P* and *S* waves. The attenuation decrement was calculated as follows [11, 31, 32]:

$$Q^{-1} = \frac{\alpha V}{8.686\pi f} = \frac{\alpha\lambda}{8.686\pi}, \qquad (1)$$

where α is absorption coefficient, dB·m^{-1},

$$\alpha(\omega) = \frac{8,686}{L}\ln\left[\frac{|R_{23}|A_{top}(f)}{|R_{12}|A_{bot}(f)}(1-R_{12}^2(f))\right], \qquad (2)$$

where L is double length of the sample, m; $A_{top}(f)$ is Fourier amplitude of the reflected pulse from the upper boundary of the sample; $A_{bot}(f)$ is Fourier amplitude of the reflected pulse from the lower boundary of the sample; $R_{12}(f)$ is coefficient of reflection from the upper boundary; $R_{23}(f)$ is coefficient of reflection from the lower boundary. In our case, the boundaries are identical and therefore $R_{12}(f) = -R_{23}(f)$. Reflection coefficient

$$R(f) = \frac{\rho_r V_r(f) - \rho_b V_b(f)}{\rho_r V_r(f) + \rho_b V_b(f)}, \qquad (3)$$

where ρ_r and ρ_b are densities of the rock and beryllium bronze, kg·m^{-3}, respectively; $V_r(f)$ and $V_b(f)$ are the wave velocities, m·s^{-1}; V is the phase velocity, m·s^{-1}; f is frequency, Hz.

When measuring a wave velocity and attenuation, the strain amplitude changed in a closed cycle. First, the amplitude increased from the minimum to the maximum value (upward course), then decreased through the same values (downward course). The full course: $\varepsilon_1 \approx 0{,}5\times10^{-6} \rightarrow \varepsilon_2 \approx 1{,}0\times10^{-6} \rightarrow \varepsilon_3 \approx 1{,}3\times10^{-6} \rightarrow \varepsilon_4 \approx 1{,}67\times10^{-6} \rightarrow \varepsilon_3 \approx 1{,}3\times10^{-6} \rightarrow \varepsilon_2 \approx 1{,}0\times10^{-6} \rightarrow \varepsilon_1 \approx 0{,}5\times10^{-6}$. The increase and subsequent decrease in the amplitude are marked with arrows in all Figures. The pulse recording was carried out with the accumulation of signals (responses). This provided improved noise immunity.

Research Findings

Figs. 1 and 2 show the dependence of *P* and *S* wave velocities on the strain amplitude in dry and water-saturated (50 %) sandstone at a constant pressure of 20 MPa. In Fig. 1, in dry sandstone, on the ascending and descending courses of the strain amplitude, P-wave velocity increases by 1.12 %. In water-saturated sandstone, the change in wave velocity under the same conditions is 0.28 %. The velocity diagrams represent open hysteresis loops (marked with brackets). The open hysteresis of dry and water-saturated sandstone is 1.41 and 0.28 %, respectively. The change in S-wave velocity under the same measurement conditions did not exceed 0.35 %. The open part of the hysteresis loop for dry and water-saturated sandstone is 0.54 and 0.35 %, respectively.

Fig. 3 shows the attenuation of *P*-wave as a function of the strain amplitude in dry and water-saturated sandstone at constant pressure. In dry sandstone, when the amplitude changes from the minimum to the maximum value, the attenuation of the wave increases in a non-linear way by 5.43 %. When the amplitude returns to the minimum value, the attenuation decreases to the initial value. As a result, the attenuation hysteresis loop is closed. In water-saturated sandstone, an increase in amplitude has little effect on attenuation. On the reverse course of the amplitude, the attenuation decreases by 4.93 %. This leads to the appearance of an open hysteresis loop. The water-saturated sandstone attenuation curve is above that for dry sandstone.

Fig. 4 shows the attenuation of *S*-wave as a function of the strain amplitude in dry and water-saturated sandstone at constant pressure. The curves for dry and water-saturated sandstone are significantly spaced apart. The value of wave attenuation in dry sandstone is much less than in water-saturated sandstone. In both cases, as the amplitude increases, the attenuation decreases. In dry and water-saturated sandstone, the attenuation reduction is 8.81 % and 2.71 %, respectively. Both hysteresis loops are open. The value of the open hysteresis loop in both cases does not exceed 0.8 %.

Fig. 5 shows *P*-wave velocity as a function of confining pressure in dry and water-saturated sandstone at constant strain amplitude. With an increase in the confining pressure from the minimum to the maximum value both in dry and water-saturated sandstone, the wave velocity increases in a non-linear way by 15.06 and 26.35 %, respectively. In both cases, an open hysteresis loop is observed: for dry sandstone, 9.77 %, and for water-saturated one, 15.93 %. Fig. 6 shows S-wave velocity as a function of confining pressure in dry and water-saturated sandstone at a constant strain amplitude. Here, the increase in the wave velocity proceeds in the same way as in the case of *P*-wave, and amounts to 12.42 % for dry sandstone, and 15.81 % for water-saturated sandstone. The open hysteresis for dry sandstone is 0.67 %, and water-saturated is 3.45 %.

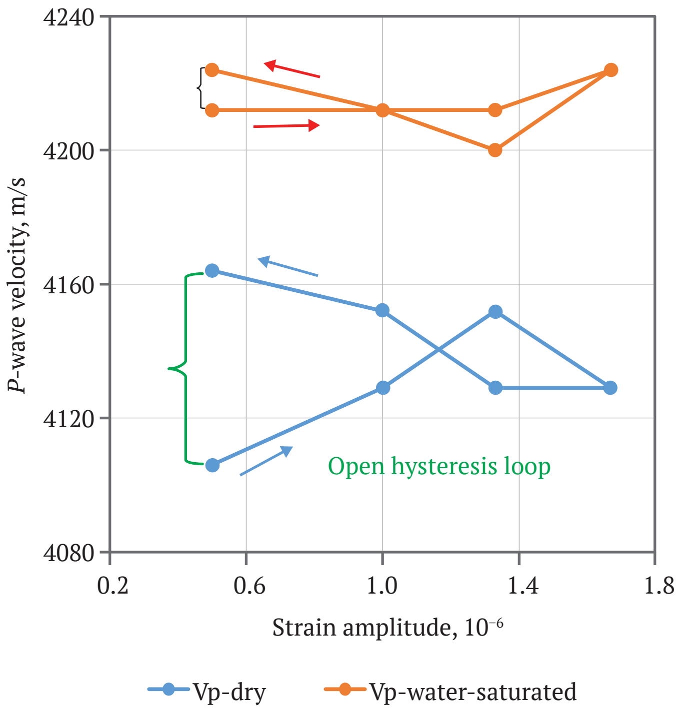

Fig. 1. *P*-wave velocity versus strain amplitude in dry and water-saturated sandstone

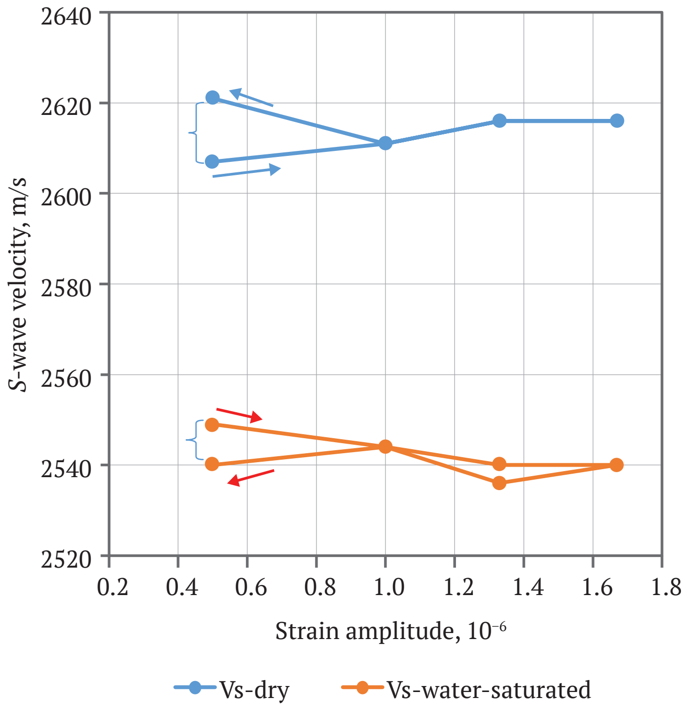

Fig. 2. *S*-wave velocity versus strain amplitude in dry and water-saturated sandstone

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Findings Discussion

The conducted study shows the complex effect of strain amplitude, pressure, and sandstone state on the behavior of the velocity and attenuation of *P* and *S* waves. Wave attenuation is more sensitive to amplitude deviation and sandstone wetness than wave velocity. The behavior of the velocity of a longitudinal wave differs significantly from that of a transverse one. The measurements of P-wave velocity show that the change in the state of sandstone affects the shape of the hysteresis and the magnitude of its opening. The open part of the hysteresis for a longitudinal wave is 1.41 % in dry sandstone and 0.28 % in water-saturated one, i.e.

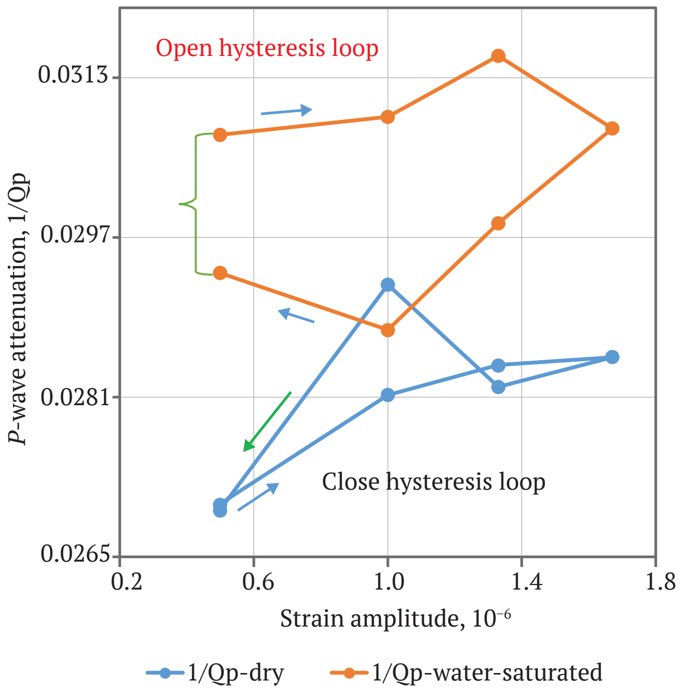

Fig. 3. Attenuation of *P*-wave depending on strain amplitude in dry and water-saturated sandstone

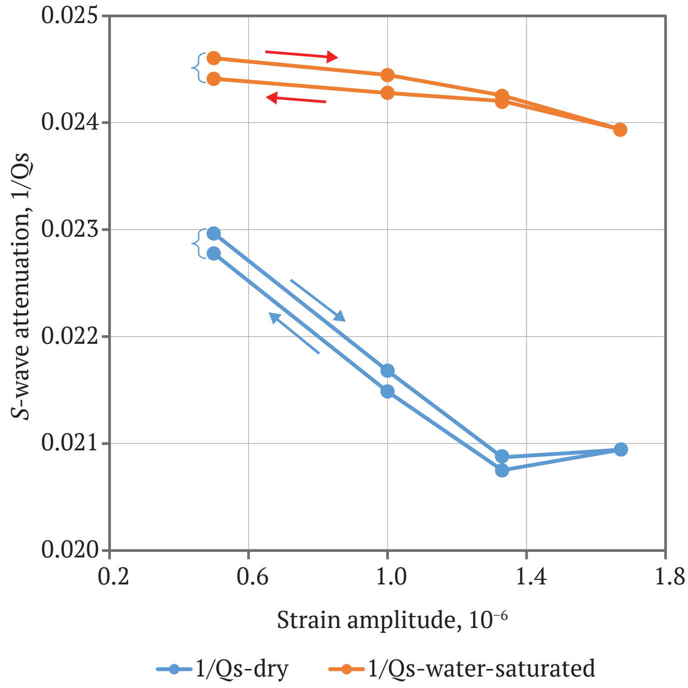

Fig. 4. Attenuation of S-wave depending on strain amplitude in dry and water-saturated sandstone

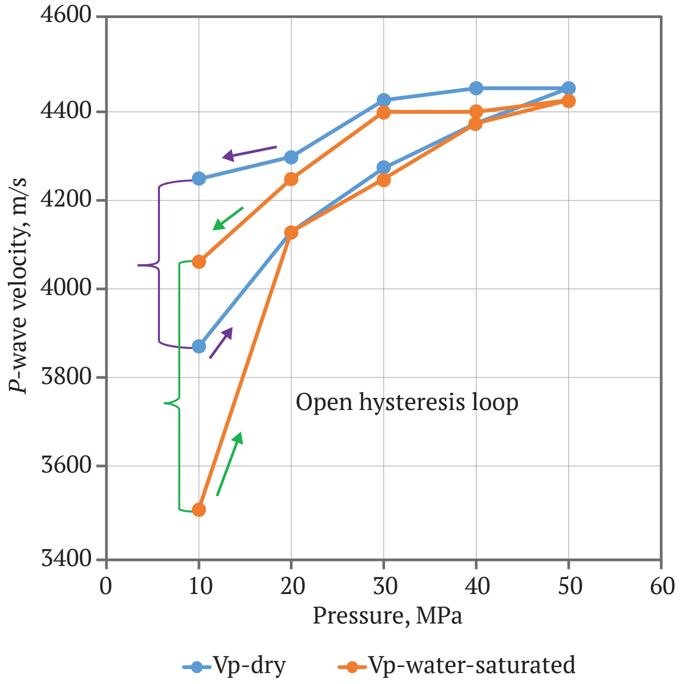

Fig. 5. *P*-wave velocity as a function of confining pressure in dry and water-saturated sandstone

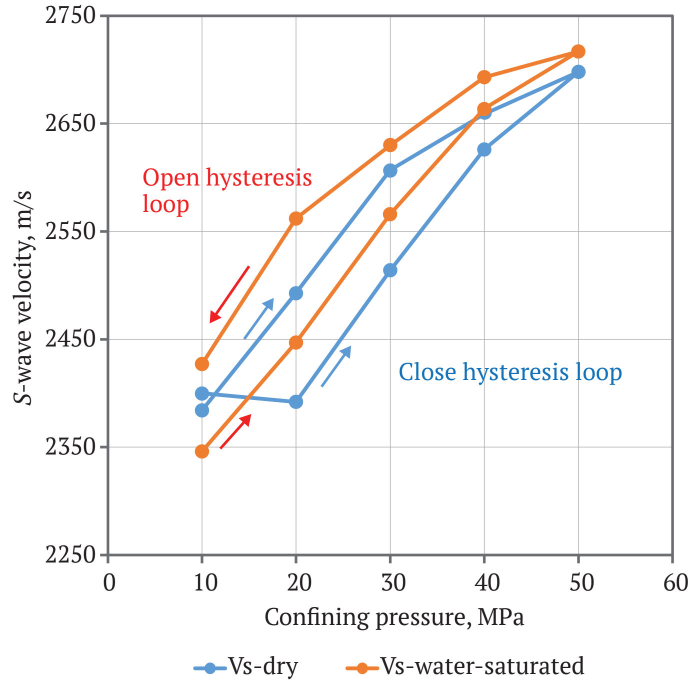

Fig. 6. *S*-wave velocity as a function of confining pressure in dry and water-saturated sandstone

there is a great difference between them. S-wave velocity in both dry and water-saturated sandstone responds weakly to amplitude deviation.

The greatest change in the attenuation of a longitudinal wave due to the strain amplitude was obtained in dry sandstone (5.43 %), the same as that of a transverse wave at the same sandstone state (8.81 %). The change in the attenuation of a transverse wave in water-saturated sandstone due to the amplitude reaches 2.71 %. For a longitudinal wave, an open hysteresis was recorded in the water-saturated sandstone (4.5 %), while it is not manifested in the dry one. For a transverse wave, both in dry and water-saturated sandstone, the manifestation of open hysteresis is insignificant. A change in the confining pressure in a closed regime for both longitudinal and transverse waves leads to a non-linear increase in the velocity and the appearance of an open hysteresis loop. It should be noted that the velocities of longitudinal and transverse waves at both states of sandstone respond to the changes in the value of the confining pressure.

Conclusion

An analysis of the new data obtained in the experiment shows the complex nature of the behavior of the velocity and attenuation of longitudinal and transverse waves depending on the strain amplitude and wetness of the sandstone. Changing the strain amplitude and confining pressure within a closed cycle (i.e. its increase and adequate decrease) leads to a significant change in the dynamic characteristics of the recorded response. This transformation takes place for wave velocity and attenuation. The strain amplitude affects the open and closed type hysteresis both for a wave velocity and attenuation. In both dry and water-saturated sandstone, an open hysteresis loop is observed in most cases. There are cases of the manifestation of a closed hysteresis loop and also the effect of overlapping hysteresis loops. The greatest change in wave velocity due to strain amplitude was obtained for a longitudinal wave in dry sandstone. However, the attenuation parameter exceeds the achievements of the wave velocity. The highest result for the amplitude-dependent attenuation was obtained in dry sandstone with the propagation of a longitudinal wave, 5.43 %, and with the propagation of a transverse wave, 8.81 %.

In our study, the signs of the manifestation of microplasticity include the following: open and closed hysteresis found in amplitude-dependent velocity and attenuation in dry and water-saturated sandstone; non-linear nature and overlap of the ascending and descending amplitude courses. Their divergence may be caused by the effect of microplasticity. The complex and peculiar behavior of both hysteresis loops suggests the possibility of contribution of a non-standard mechanism in the sandstone strain. The diverse behavior of wave velocity and attenuation at rock strain can be caused by the combined effect of viscoelasticity and microplasticity processes. The qualitative and quantitative characteristics of the complications of dynamic parameters can be the signs of the internal structure of the subject.

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