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Amplitude-dependent hysteresis of wave velocity in rocks in wide frequency range: an experimental study

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Abstract

This research belongs to the field of rock physics. In recent years, in solid state physics and materials science, new knowledge has emerged about microplastic strain of various materials, including rocks. These data were obtained using high-precision micro- and nanoscale strain measurements. The very fact of the existence of the poorly studied rock property in the earth sciences requires the study of the possible influence of the rock microplasticity on the propagation of seismic and acoustic waves. The studies were carried out using three alternative methods and under different observation conditions. The field measurements were carried out in the zone of low velocities in crosshole space with transmitted waves of frequency of 240–850 Hz. The laboratory measurements were carried out on sandstone samples with transmitted (6.8 kHz) and reflected (1 MHz) waves at the strain of 10^{-8}–10^{-6}. The manifestations of microplasticity were recorded using high-resolution recording of signals with discretization time $t_{discret}$ = 1 μs – 40 μs and 32.5 ns. The wave amplitude variation was provided in a closed cycle: discrete increasing the amplitude from minimum to maximum and return to the initial value (A1+ → A2+ → … A_{max} … → A2– → A1–). In this amplitude range, an amplitude hysteresis was observed, a sign of which was the inequality of wave velocities on the upward and downward amplitude courses. This effect was recorded for all three measurement methods at different frequencies. However, the amplitude hysteresis of the wave velocity was not observed only in the measurements at full water saturation of loam. The largest amplitude-dependent change in the wave velocity reached 2% (at the accuracy of 0.02%), and the change in the attenuation value amounted to 5%. The reason for this effect could be microplastic inelasticity, which manifested itself by amplitude plateaus located within the waveform. The amplitude microhysteresis forms overall picture of the amplitude dependence of the wave velocity in wide amplitude range. Proposals for the potential use of the obtained data for solving some applied problems have been presented.

Key words

rock physics, wave processes, elastic modulus, wave attenuation, wave velocity hysteresis, microplastic strain, discontinuous inelasticity, amplitude dependence of wave velocity

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СВОЙСТВА ГОРНЫХ ПОРОД. ГЕОМЕХАНИКА И ГЕОФИЗИКА

Научная статья

Амплитудно-зависимый гистерезис скорости волны в горных породах в широком диапазоне частот: экспериментальное исследование

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Аннотация

Это исследование относится к области физики горных пород (Rock Physics). За последние годы в физике твердого тела и материаловедении появились новые знания о микропластической деформации различных материалов, в том числе горных пород. Эти данные получены с помощью высокоточных измерений деформации на микро- и наноуровне. Сам факт существования мало изученного в науках о Земле свойства горных пород требует изучения возможного влияния микропластичности пород на распространение сейсмических и акустических волн. Исследования проведены по трем альтернативным методикам и при различных условиях наблюдения. Полевые измерения проведены в зоне малых скоростей в межскважинном пространстве на проходящих волнах частотой (240–850) Гц. Лабораторные измерения выполнены на образцах песчаника на проходящих (6,8 кГц) и отраженных волнах (1 МГц) при деформации (10^{-8}–10^{-6}). Проявления микропластичности зарегистрированы с использованием высокоразрешающей записи сигналов с временем квантования $t_{квант}$ = 1 мкс – 40 мкс и 32,5 нс. Вариация амплитуды волны осуществлялась по замкнутому циклу: дискретное увеличение амплитуды от минимума до максимума и возврат к исходной величине (А1+ → А2+ → … $А_{макс}$ … → А2– → А1–). В этом амплитудном диапазоне имеет место амплитудный гистерезис, признаком которого является неравенство скоростей волн на восходящем и нисходящем амплитудном курсе. Этот эффект зарегистрирован для всех трех методов измерения на разных частотах. Однако амплитудный гистерезис скорости волны отсутствует только в случае измерений при полном водонасыщении суглинков. Наибольшее амплитудно-зависимое изменение скорости волны достигает 2 % (с точностью 0,02 %), а изменение величины затухания составляет 5 %. Причиной такого эффекта может быть микропластическая неупругость, признаками которой являются амплитудные плато, располагающиеся внутри формы волны. Амплитудный микрогистерезис формирует общую картину амплитудной зависимости скорости волны в широком амплитудном диапазоне. Представлены предложения возможного применения полученных данных для решения некоторых прикладных задач.

Ключевые слова
физика горных пород, волновые процессы, затухание волн, гистерезис скорости волны, микропластическая деформация, скачкообразная неупругость, амплитудная зависимость скорости волны

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Introduction and Challenge Problem

A promising approach to increasing geological efficiency of seismic and acoustic research methods is based on new knowledge in the rock straining physics. This means deep study of the mechanisms of micro- and nanoscale propagation and attenuation of elastic waves. The list of little-known phenomena includes rock microplasticity, which manifests itself at small-scale strains. Wide frequency range of quasi-static and dynamic stresses and strains is of Interests.

Dynamic characteristics of rocks under seismic impacts were studied at large and moderate strains [1]. With studying nonlinear effects in seismic [2–7], the problem of the “elasticity – inelasticity” boundary has become more actual. Taking into account (proceeding from) the experimental data, the boundary strain level was gradually shifted from ~10^{-2}–10^{-3} towards lower strains to ~10^{-6}. Thus, it was shown that nonlinear effects in rocks are possible even at small strains. This extends the effect of inelastic processes to the field of practical application, where low-intensity waves are used.

At present, seismic theoretical studies are based on the classical viscoelastic model of a standard linear body, which describes well dispersion, relaxation, and related inelastic processes [8, 9]. However, this model does not take into account such a non-standard effect as the amplitude dependence of wave velocities and attenuation, which was found in many experiments in the course of propagation of seismic and acoustic waves in rocks [10–13]. These were mainly laboratory experiments on hard rock samples extracted from great depths. The experimental data showed that, with increasing the transmitted signal amplitude, decreasing the wave velocity and increasing the attenuation were observed [9, 14, 15]. Other experiments also confirmed the data presented above, but at the same time showed opposite results as well. With increasing the transmitted signal amplitude, both increasing and decreasing the wave velocity and attenuation could occur [6, 11]. The unusual behavior of wave velocities extends to the elastic modulus behavior. The decrease or increase in the elastic modulus took place in accordance with the stress-strain ratio slope of curve [16 –20].

Microplastic inelasticity of rocks was discovered in quasi-static experiments on various samples [19]. Microplasticity of metals, alloys and other materials has been known. Its manifestations on the “stress-strain” diagram are presented in the form of “the stress-plateau” and “the stress-drop” [21–24]. This phenomenon can be characterized as some irregular short-term “actuation” of plasticity within the elastic strain range [16, 25–27]. This thesis has also theoretical substantiation [28, 29]. Below the findings of the P-wave velocity amplitude dependence study in the rocks obtained using different equipment under different experimental conditions are presented.

Research Techniques and Factual Material

Field studies

Field measurements were carried out in a zone of low velocities in loams. In the upper part to a depth of 8.5 m, the rocks were partially water-saturated. P-wave velocity was about 340 m/s. Below there was an aquifer, the wave velocity in which was ~ 1500 m/s. The measurements were carried out using the cross-hole test; the distance between the holes was 7m. In the first spread, the transmitter was installed at a depth of 2 m, and the signal receiver, at a depth of 10 m (2 m – 10 m). The wave mainly travelled through partially water-saturated rock. At the second spread, the transmitter and receiver were at a depth of 10 m – 10 m, the wave propagated in a rock completely saturated with water.

The seismic signal transmitter consisted of a set of piezoelectric cells placed in a body with a preamplifier [4, 30]. The signal was transmitted through a liquid spacer and a sealed elastic shell that contacted the hole wall. The pulse amplitude on the piezoelectric transducer of the transmitter varied from 350 to 950 V. PDS-21 sensor was used, which had conversion ratio of 100 µV/Pa. The signal receiver was in contact with the hole walls through the elastic liquid spacer. Recording was carried out with signal accumulation up to 128. The signals were digitally recorded on a computer. The measurement accuracy of the pulse propagation time was ~0.02%. The recording discretization time $t_{discret}$ = 8 µs and 40 µs. The strain amplitude range was $(3.8 – 9.8) \times 10^{-8}$.

Laboratory measurements in low kilohertz frequency range

The experiments were performed on a cylindrical sandstone sample 76 mm in diameter and 1 m long. The rock density was 2.0 g/cm^3, the porosity was about 3%. The P-wave propagation speed was 2910–3000 m/s. The experiment was carried out at room temperature at five values of the strain amplitude in the range of: $(0.3–1.67) \times 10^{-6}$.

The transmitter and receiver of the acoustic signals consisted of piezoceramic cells (TsTBS-3), were rigidly mounted on one end of the sample cylinder. At the other end of the sample, a brass washer 3 mm thick was rigidly fixed in the same way. The entire structure was inserted through a jack into the wall opening. The acoustic pulse with frequency of 6835 Hz, having passed along the sample, was reflected from the opposite end and arrived at the receiver and, through the amplifier, at the digital recording device. The ADC recorder discretization time was 1 µs. The wave velocity measurement accuracy was 0.05%. The relative measurement accuracy determined with the amplitude variation and the other conditions constancy was much higher.

Laboratory measurements at frequency of about 1 MHz

The research was carried out on samples of dry sandstone of cylindrical shape 2.4 cm long and 4.0 cm in diameter. The fine-grained sandstone with the presence of siltstone was sampled from hole at a depth of 2,920 m. The rock density was 2.36 g/cm^3, the total porosity was 13%. The measuring installation was a three-layer model. The first and third layers (beryllium bronze) provided identical wave reflection at the interfaces. The first layer acted as a delay line, and the third layer acted as an acoustic load. The rock sample was located in between these layers. Excitation and reception of signals was provided by piezoceramic sensors at frequency of ~ 1 MHz, which were polarized to longitudinal wave. Controlled static pressure (20 MPa) ensured constant contact at the boundaries of the layers.

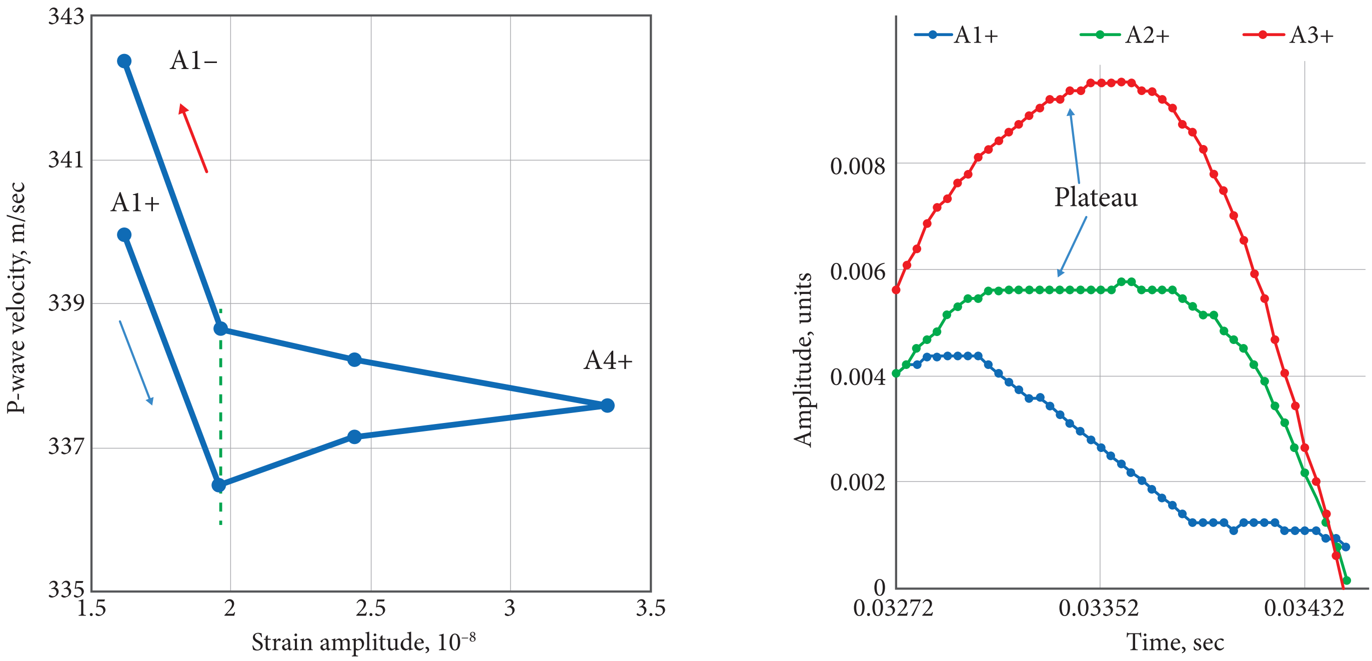
Research Findings

Field testing

The behavior of the P-wave velocity depending on the strain amplitude in the loams is presented for two source and receiver arrangements: the abovementioned spreads of (2 m – 10 m) and (10 m – 10 m). Fig. 1, *a* presents the dependence of the P-wave velocity on the amplitude when the source was located at a depth of 2 m, and the receiver, at a depth of 10 m. The magnitude of the transmitted signal amplitude varied discretely in a closed cycle. The amplitude increased from A1, A2, A3 to A4 (ascending half cycle), and then its decreased through the same values to A1 (descending half cycle) – and we had got a set of digital records in the full cycle.

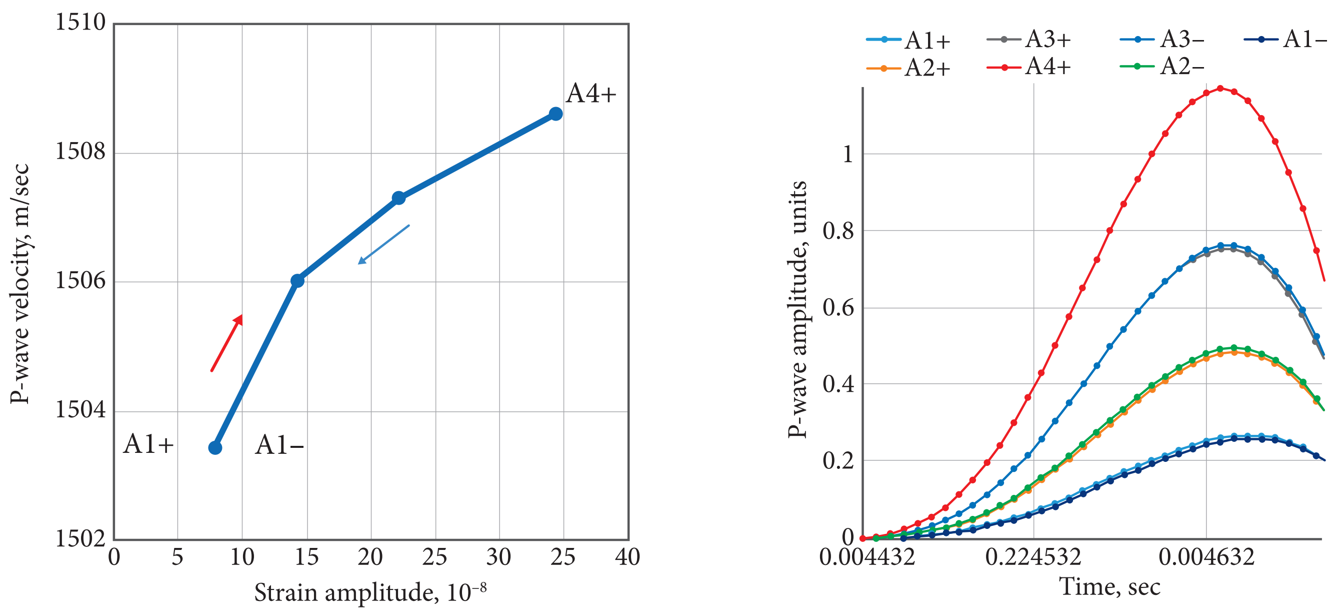
The behavior of the P-wave velocity in the loams depending on the strain amplitude was complicated. In the first half cycle of the amplitude course, the wave velocity first decreased and then increased nonlinearly. In the second half cycle, the wave velocity non-monotonically increased. The largest change in the wave velocity in the cycle was 1.7%. There was a clear divergence of the wave velocity "paths" between the upward and downward half cycles. In the A2–A4 range, the wave velocity increased instead of decreasing. Upon completion of the full cycle, we received an open hysteresis loop, which amounted to 0.7%. This was the effect of the amplitude-dependent hysteresis of the P-wave velocity.

Examination of the seismic record showed the presence of unusual complications in the waveform that have been identified as signs of microplastic strain. Individual fragments of the pulses recorded at the three amplitude values are shown in Fig. 1, *b*. These are built-in short-term amplitude plateaus, the length of which ranged from one to several $t_{discret}$ = 40μs. The instantaneous value of the pulse amplitude did not change over the length of the plateau. These plateaus interrupted the "normal" amplitude course, i.e. the process of elastic strain and the transition to microplastic flow. The plateau length reached twelve $t_{discret}$ or 480 μs. The increase in the number of plateaus leaded to decreasing the pulse front steepness and the pulse pulling. The dependence of the P-wave velocity on the amplitude of strain in the loams at the (10 m – 10 m) spread is shown in Fig. 2, *a*. With increasing the amplitude from A1 to A4, the



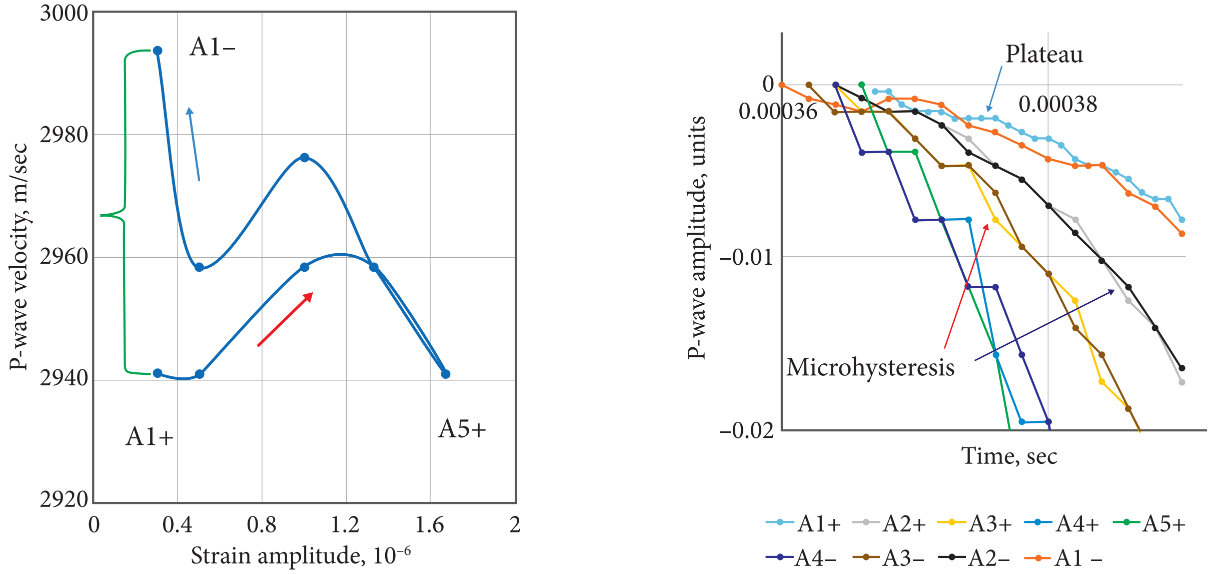
a *b*

Fig. 1. P-wave velocity in loams depending on the strain amplitude: source at a depth of 2 m, receiver at a depth of 10 m (*a*). Fragments of the impulses with complications in the form of plateau (*b*)



a *b*

Fig. 2. The P-wave velocity depending on the strain amplitude at the source-receiver spread of 10 m – 10 m (*a*). Fragments of the pulse front at the A1–A4 amplitudes at the source-receiver spread of 10 m – 10 m (*b*)



a *b*

Fig. 3. Fragments of the pulse front at the A1–A4 amplitudes at the source-receiver spread of 10 m – 10 m (*a*). Plateau manifestation (b). Fragments of the pulses recorded at five amplitudes in the first arrival region (*b*)

P-wave velocity increased nonlinearly by 0.34%. Here, unlike the previous spread, no amplitude hysteresis was observed. This was an interesting feature of the wave propagation in the fully water-saturated loams. The digital records also showed no plateau on the waveform (Fig. 2, *b*).

Laboratory experiment at low kilohertz frequencies

P-wave velocity in the sandstone depending on the ascending and descending strain amplitudes is shown in Fig. 3, *a*. As the amplitude increased from A1+ to A5+, the wave velocity first increased and then decreased. When the amplitude decreased from A5+ to A1–, the wave velocity increased with a large dip, and an open hysteresis loop was observed, which amounted to 1.8%. Fig. 3, *b* presents the fragments of the pulse front near the first arrival for the five values of the upward and downward strain amplitude. The acoustic paths had plateaus longer than $t_{discret}$ = 2 μs. These built-in plateaus altered the overall slope of the pulse front.

Microhysteresis was found on the wave profile. This was a short-term deviation of two identical traces (for example, A1+ and A1–, A2+ and A2–, etc.) from the general amplitude course, Fig. 3, *b*. In this case, the front slope (i.e. strain rate) changed in a small leg. Such legs of microhysteresis alternated with the legs of complete coincidence of the upward and downward courses.

Laboratory experiment at frequency of about 1 MHz

The dependence of the wave velocity on the strain amplitude is shown in Fig. 4. With increasing the amplitude, the P-wave velocity value demonstrated

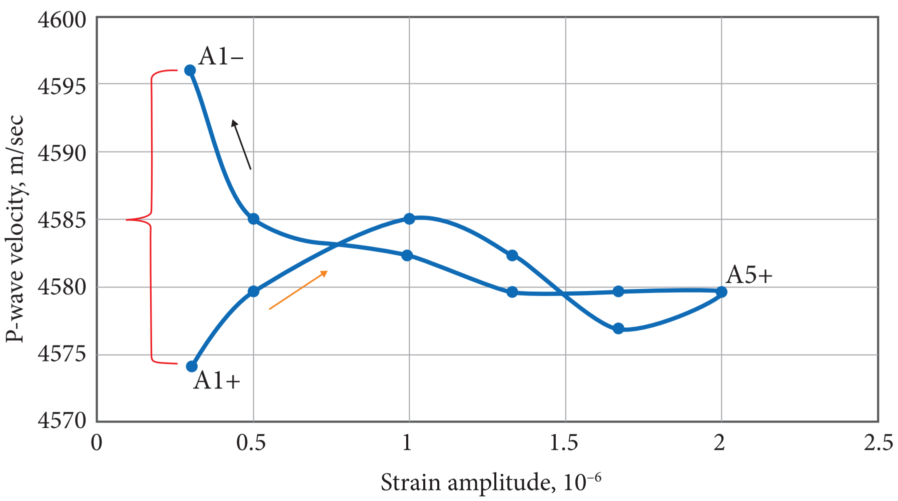


Fig. 4. P-wave velocity in sandstone depending on strain amplitude

wave-like behavior. With decreasing amplitude, the wave velocity increased nonlinearly by 0.36%. The amplitude hysteresis was 0.48%. The shape of the reflected pulses recorded with nanosecond resolution at six amplitude values in the closed measurement cycle evidenced a complicated strain pattern. Fig. 5 presents a fragment of the wave front, where one can see non-standard inelastic manifestations in the form of a plateau, local amplitude drop, and microhysteresis. The duration of these complications amounted to several $t_{discret}$ = 32.5 ns. It should be noted that the records (traces) with upward (A+) and downward (A–) amplitudes, despite some deviations, generally coincide.

Findings Discussion

The effect of microplasticity depends in a complicated fashion on the strain level (the magnitude of the applied mechanical action). The experiments carried out under different conditions showed basically the same results. This confirmed the fact that the strain amplitude influenced the P-wave velocity. The change in the P-wave velocity due to the amplitude influence reached 2%. The latest studies carried out on rock samples using high-precision laser Doppler interferometry showed that the change in wave velocity due to the amplitude influence reached 5% [12, 14, 27].

The amplitude effect was detected at high seismic and kilohertz frequencies with dynamic strains of about 10^{-8}–10^{-6}, which related to the region of high strain rates. However, the previously obtained results of the quasi-static experiments [16, 20, 26, 28] indicated the possibility of such effect at lower frequencies. Low rates of a solid body straining create even more favorable conditions for the actuation of the microplasticity mechanism [17, 22]. It was detected that at low strain amplitudes, the magnitude of the amplitude hysteresis was greater than at higher amplitudes.

The experiments showed the "overlapping" of the hysteresis loops, and hence the observed increase or decrease in the wave velocity (elastic modulus). A small change in the signal amplitude magnitude (one discrete step ΔA_i) could lead to a noticeable change in the wave velocity. The standard (generally accepted) viscoelastic model for rocks does not allow such behavior of the elastic modulus. The microhysteresis effect requires in-depth study, since its influence on the wave dynamic parameters can be significant.

Conclusion

The amplitude hysteresis effect can be useful for practical applications. The absence of hysteresis in a fully water-saturated rock encourages repeated experiments with this result in mind. The established effect of the local change in the wave velocity in the small range of strain amplitudes is of both fundamental and practical importance. Currently, in seismic methods, the wave velocity sensitivity to the

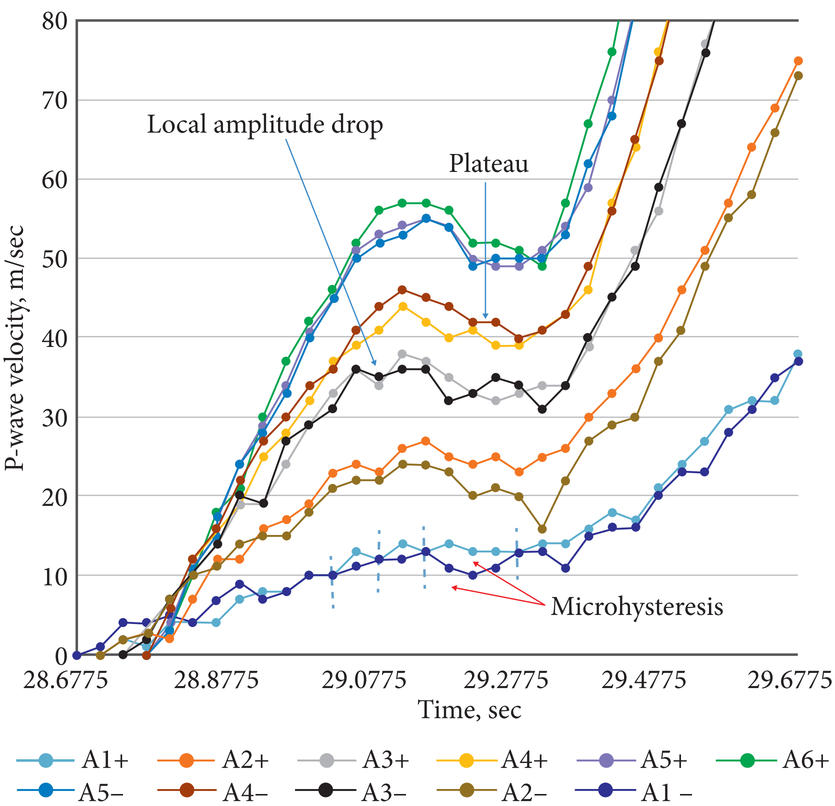


Fig. 5. Fragments of the pulse front in sandstone at six amplitude values

transmitted signal magnitude is not taken into account that reduces the survey accuracy.

In conclusion, we can say that organizations interested in this issue, if they wish, can check the feasibility of applying the amplitude-dependent effect in practice and determine its usefulness for further use. This check does not require any special equipment.

The equipment used for common field work can be used for the check (with some additions). At the very least, high-precision digital recorders are available for the experimentation. Changing the wave amplitude magnitude is methodically achieved, for example, by successively changing the power of the wave transmission source. Consideration of the amplitude factor can be useful, for example, to reduce errors when constructing a seismic cross-section and in other areas of geophysical surveys. The potential areas of the effect validation and application are seismic exploration, VSP, acoustic logging and others.

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