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Effects of Intermittent Inelasticity when Propagating Seismic Wave in Low Velocity Zone

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Abstract: The study of atypical manifestations of rock inelasticity improves understanding of the physical mechanisms of seismic wave propagation and attenuation in real environments. In the field experiments, the propagation of longitudinal wave at frequency of 240–1000 Hz between two shallow boreholes in low speed zone was investigated. The measurements were performed using a piezoelectric pulse emitter and similar receiver tools positioned in the boreholes. "Stress-time" $\sigma(t)$ digital responses were recorded by the open channel with microsecond temporal resolution. The unusual short-period variations of amplitude in the form of sharp flattening wave front, stress drop, or plateau of different width (tens of microseconds) were detected in the wave profile. These low-amplitude variations in the waveform were regarded as manifestations of hopping intermittent inelasticity. This inelastic process was assumed to affect the waveform transformation. The contribution of hopping inelasticity depends on the applied stress magnitude, i.e. in this case, the seismic response amplitude. The mechanism of hopping inelasticity at small strains may be explained by microplasticity of rocks. The findings obtained represent a new step in understanding of physics of seismic and acoustic wave propagation in rocks and can be useful for handling of applied problems in geophysics and mining.

Keywords: hopping strain, rock microplasticity, inelastic seismic attributes, amplitude dependence of wave velocities and attenuation.

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Эффекты прерывистой неупругости при распространении сейсмической волны в зоне малых скоростей

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Аннотация: Изучение нетипичных проявлений неупругости горных пород расширяет понимание физических механизмов распространения и затухания сейсмических волн в реальных средах. Полевые эксперименты выполнены при распространении продольной волны частотой 240–1000 Гц в пространстве между двумя неглубокими скважинами в зоне малых скоростей (ЗМС). Измерения проводились с помощью пьезоэлектрического импульсного излучателя и аналогичных приемников, размещенных в скважинах. Цифровые записи сигналов в виде «напряжение-время» $\sigma(t)$ регистрировались открытым каналом с микросекундным разрешением во времени. На профиле волны обнаружены необычные короткопериодные вариации амплитуды в виде резкого уменьшения крутизны фронта, падения напряжения или плато различной длительности (десятки микросекунд). Эти малоамплитудные вариации на форме волны были расценены как проявления скачкообразной прерывистой неупругости. Сделано предположение, что этот неупругий процесс оказывает влияние на трансформацию формы волны. Вклад скачкообразной неупругости зависит от величины прикладываемого напряжения, т.е. в нашем случае от величины амплитуды сейсмического сигнала. Возможный механизм скачкообразной неупругости на малых деформациях может быть объяснен микропластичностью горных пород. Полученные результаты представляют новый шаг в понимании физики распространения сейсмических и акустических волн в горных породах и могут быть полезными для решения прикладных задач в геофизике и горном деле.

Ключевые слова: скачкообразная деформация, микропластичность горных пород, неупругие сейсмические параметры, амплитудная зависимость скоростей волн и затухания.

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Introduction

The study of the physical manifestation of seismic waves propagation and attenuation mechanisms, despite its long history, is still a crucial task. To solve this problem, the modern approach uses new knowledge on rock strain obtained at the micro-scale level. The classical viscoelastic model describes dispersion and relaxation well [5, 23]. However, this model does not explain the mechanism, for example, of the ambiguity of the amplitude dependence of the wave velocity and attenuation. This suggests the existence of some disregarded inelasticity mechanism.

The study of the dynamic characteristics of rocks is quite fully described in [2]. The data were obtained at large and moderate strains, however, amplitude and other atypical effects are not considered here. The study of nonlinear effects in seismic showed the possibility of their action even at small strains [4, 8]. These works gave impetus to the further study and search for the physical causes of these effects.

A review of the amplitude dependence of wave velocities and attenuation [26] presents experiments performed on rock samples under harmonic oscillations, and theoretical ideas. Most data indicate decreasing wave velocity and increasing attenuation with increasing amplitude [23, 31, 34]. A few data for rocks show, on the contrary, increasing wave velocity and decreasing wave attenuation with increasing amplitude [20, 37]. The possibility of non-standard behavior of wave velocities was substantiated in theoretical studies [24, 20; 18]. It is shown here that a decrease or increase in the modulus of elasticity occurs in accordance with the positive or negative nature of the $\sigma(\varepsilon)$ graph curvature.

There are few field experiments on the amplitude dependence of wave velocities, which were carried out in the subsoil layer in shallow pits or on the shore of a reservoir [37]. The records show that as the signal amplitude increases, the wave velocity may both increase and decrease. There is also a residual hysteresis of the wave velocities that indicates irreversible strains caused by the seismic wave. Unusual data on the amplitude dependence were also obtained in the laboratory experiments [7]. It was found that in dry and water-saturated sandstone in the ultrasonic frequency range, the attenuation parameter is more sensitive to amplitude variations than the wave velocity.

The data indicate that non-standard effects are due to defective rocks, demonstrating microheterogeneity, the presence of thin films, microcracks, and the complexity of the phase composition. The experiments using modern equipment for recording the wave process and electron microscopy confirm this [19]. For example, the data for crystalline olivine show the effect of nanometer intergranular contacts on the shear wave attenuation parameter. These intergranular contacts have abnormal elasticity modulus values and cause unusual transformations of the attenuation parameter $Q^{-1}(\omega)$. Some theoretical approaches and experimental work have also been performed in this regard [35; 11; 36].

The aim of the paper is to establish the manifestations of intermittent inelasticity in rocks caused by a seismic wave, and to compare these data with the findings of quasistatic experiments and other recent studies.

The experiment techniques and procedure

The experiments were performed at the Bystrovsky field test site in the Novosibirsk Region. The upper part of the sequence (ZMS) is relatively homogeneous (there are no reflecting boundaries) and composed of loam several tens of meters thick. The loam consists of sand, silt and clay in proportions of about 40 : 15 : 45 %, respectively. The size of clay particles and sand grains is from five to tens of micrometers. The loam to a depth of ~3 m is relatively dry, to ~8.5 m partially water saturated, and then completely water saturated. The velocity of longitudinal wave in dry and partially water saturated loams is V_p = 240–500 m/s, and in fully water saturated loam $V_p \approx 1500$ m/s.

The emitting source was located in a pit about 1 m deep. The first seismic response receiver was located near the source at a distance of 0.4–1 m. The second receiver was located in the borehole at a depth of 1 m and at a distance of 6 or 14 m from the source. The pulse source consists of a set of piezoelectric disks. The predominant frequency of the emitted pulse in the near receiver is ~1100–3300 Hz, and in the distant receiver ~120–340 Hz. The emission passes through an elastic shell with a liquid, contacting with the borehole wall. The piezoelectric pressure receiver contacts the borehole wall in a similar manner that provides good contact with the medium. Seismic records is the stress as a function of time, $\sigma(t)$, quantization time t_{quant} = 20 μs and t_{quant} = 125 μs. The amplitude quantization step (A_{quant}) in the ADC is 78 mV. The amplitude values in volts were converted to mechanical stresses using the conversion factor K_{conv} = 100μ V/Pa. The seismic response receiver has a preamplifier with a gain of $K = 100$. The seismic responses in digital form were recorded on a computer. The amplitude of the input waveform (seismic responses) varied discretely from minimum to maximum: $A_1 \rightarrow A_2 \rightarrow A_3 \rightarrow A_4$. The amplitude increases as $A_2/A_1 = 1.5$; $A_3/A_1 = 2.0$; $A_4/A_1 = 2.5$. At a distance of 14 m from the source, the stress in the medium is approximately several tens of Pascals, and the strain range is ~10^{-8}–10^{-6}. These are small strains being below the conditional elastic limit.

The Findings and Discussion

The analysis of seismic records was carried out using a digital high-resolution signal (seismic response) displaying (mapping) on an enlarged scale. The mapping is obtained by connecting all the quantization points (t_{quant}) of the digital amplitude values along the seismic trace by straight lines (without smoothing). Such a representation of the signal allows a detailed analysis of the dynamic process, i.e. the process of development of stress (strain) in time. The illustrations are provided in both analog and digital imageries.

Findings

Fig. 1 shows six simultaneously received signal records in analog form, recorded at three amplitude values (A_1, A_2, A_3). Of these, three seismic traces are records of the first (closest to the source) receiver installed in the borehole at a depth of 1 m, and three seismic traces were recorded by the second receiver, located in the other borehole in 1 m from the source, at a depth of 6 m.

Analysis of the records in digital displaying shows the following. Due to the impossibility of placing the entire record in one picture, it is illustrated in separate parts. Fig. 2 shows the sections of records of the first pulse semiperiod, recorded near source *a*, and the first pulse – semiperiod at a depth of 6 m (below the source) *b*. Comparison of *a* and *b* records shows their qualitative difference.

At all amplitudes, the primary signal $\sigma_s(t)$ profile is quite smooth. The profile $\sigma_\gamma(t)$ has complications in the form of a plateau 1 of various lengths, a local stress drop 2 (marked with a dashed oval) and areas of sharp changes in the steepness of the wave 3 front (marked with arrows). Here, the front steepness changes by a factor of 9 during one t_{quant}. The listed complications are of significant expansion here.

Fig. 3 shows the sections of the records of the second (positive) semiperiod of the near pulse *a* and the similar distant pulse semiperiod *b*, recorded at a depth of 6 m. Comparison of these records produces the same result as described above. The first and repeated records at the same amplitude A_2, recorded by the distant receiver, are shown in Fig. 4. These pulses in analog form are presented in Fig. 4, *a*. A detailed picture in digital imagery can be seen at three recording intervals, where section *b* represents the record of the first minimum, sections *c* and *d* are fragments of the ascending and descending pulse fronts, respectively. Here the same non-standard manifestations take place and the same peculiarities of the first and repeated recordings are observed, which are described above. The stress drop is replaced by the flat region (in Fig. 4 it is marked by arrows in the rectangle). There are sections of the pulse front that are free from non-standard manifestations (Fig. 4, *d*).

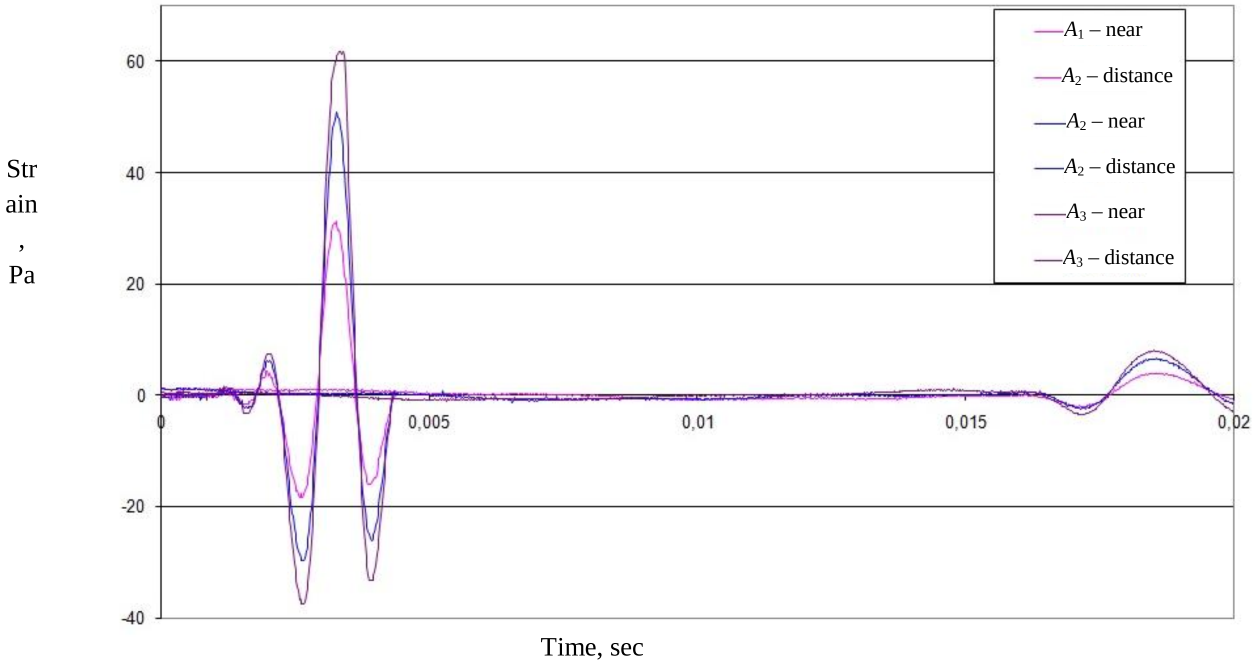

Fig. 1. Seismic response analog records at three values of amplitudes (A_1, A_2, A_3) obtained near the source (pulse emitter) and at a distance from it

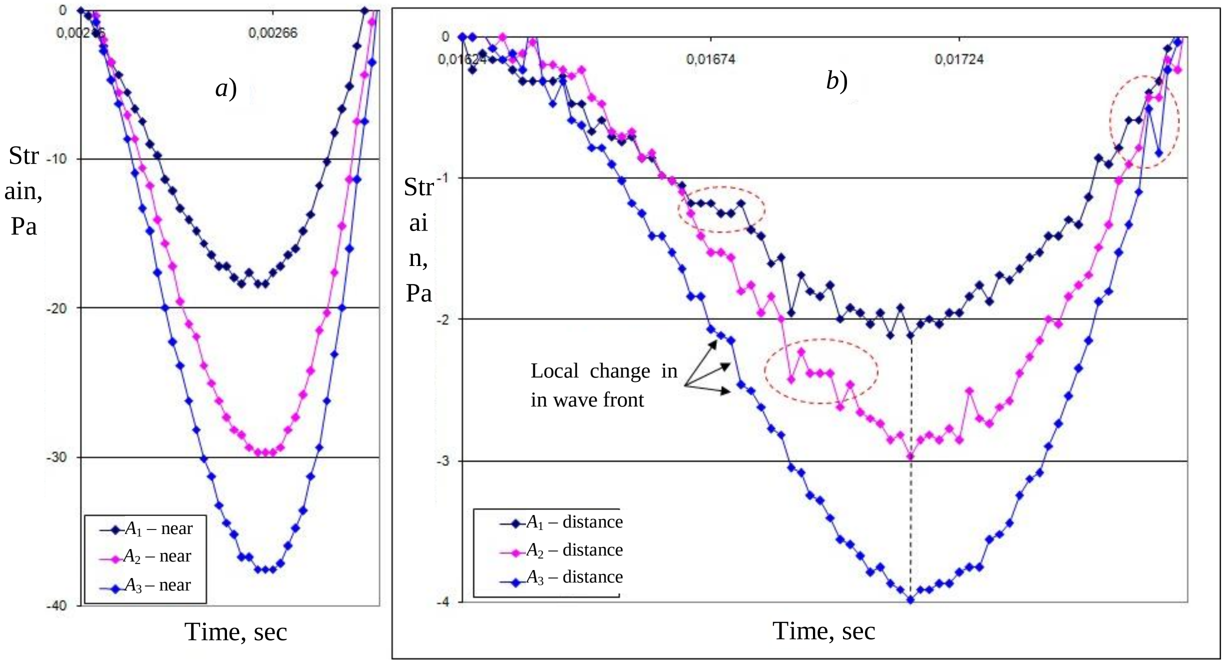

Fig. 2. Sections of the records of the first semiperiod of the pulse closest to the source (*a*) and the pulse recorded at a depth of 6 m (*b*)

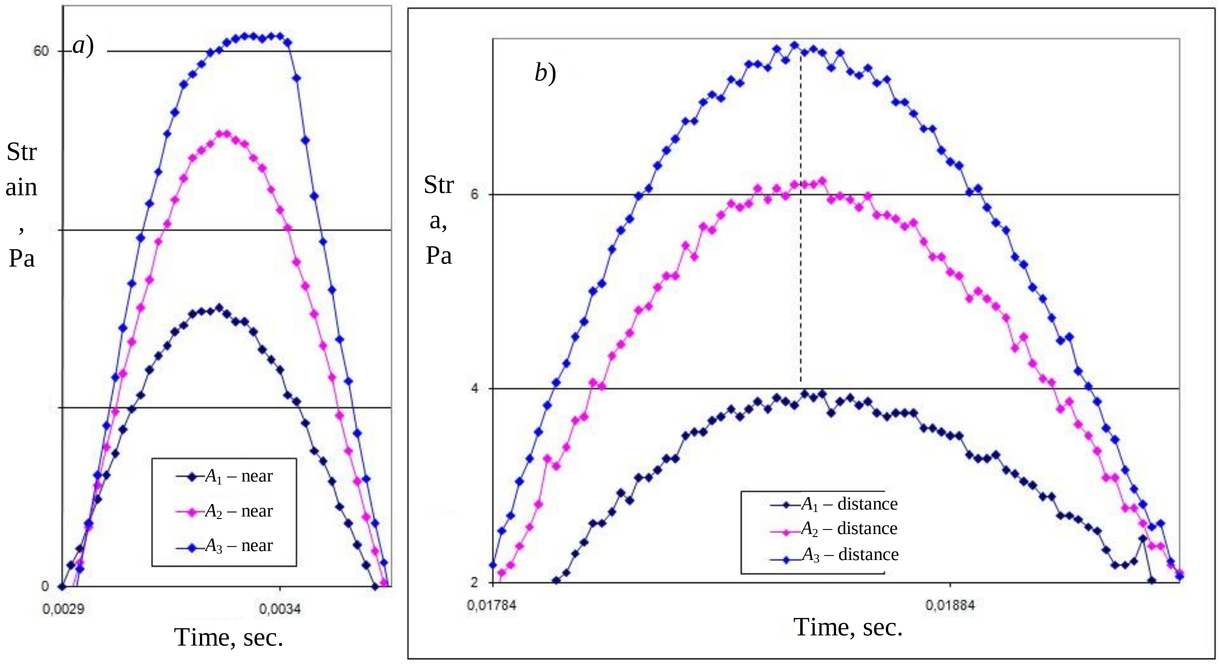

Fig. 3. Sections of the records of the positive semiperiod of the pulse closest to the source (*a*) and the analog semiperiod of the pulse recorded at a depth of 6 m (*b*)

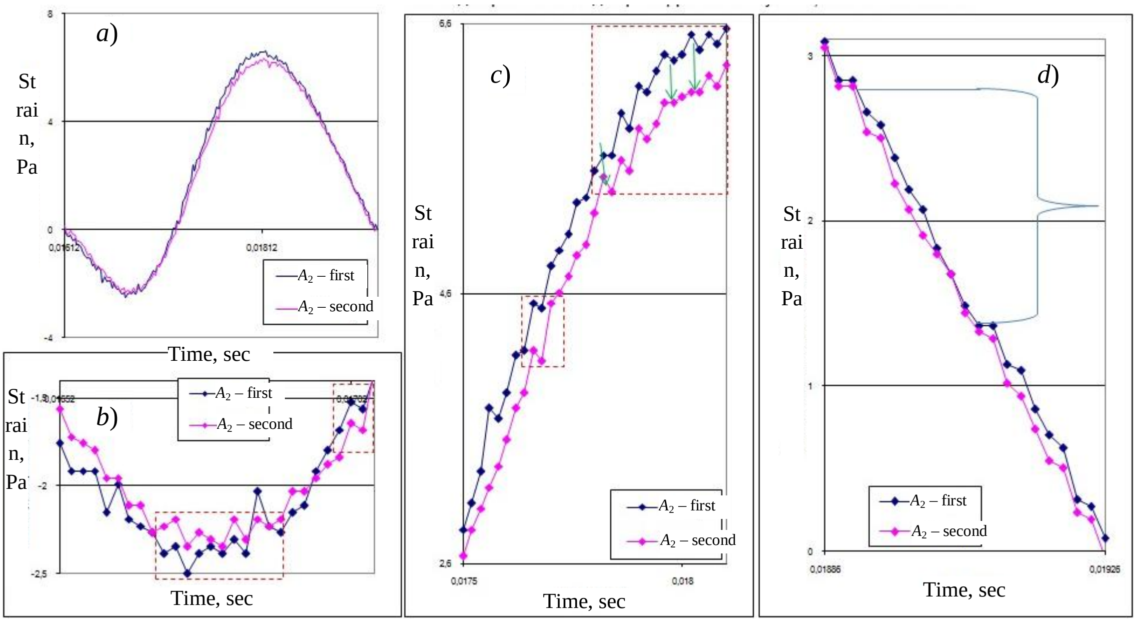

Fig. 4. The first and repeated records at the same amplitude (A_2), recorded by the far receiver tool:
a – the analog pulse record; *b* – the first minimum; *c*, *d* – fragments of the pulse ramp and downgoing front, respectively

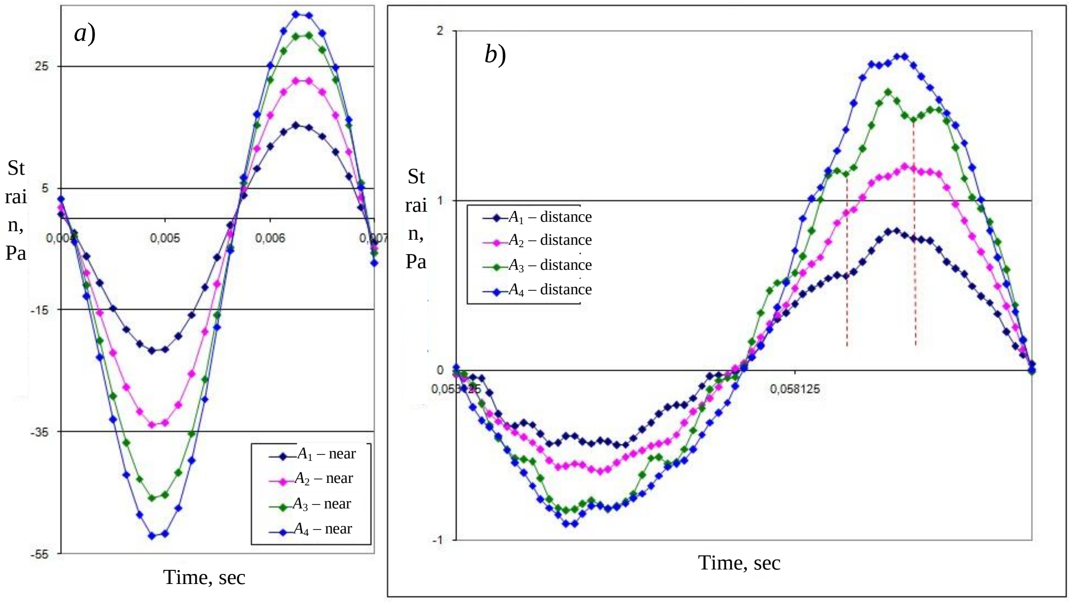

Fig. 5. Stress pulses recorded by the receiver tool closest to the source (*a*) and the far receiver (*b*), located in 1-m borehole at a distance of 14 m from the source

Fig. 5 shows the recordings of the near receiver *a* and the distant receiver *b*, located at distances of 1 m and 14 m from the source, respectively. The wave profile far from the source is complicated by the plateau and the areas of stress drop at all amplitudes. The descending front of the positive semiperiod demonstrates practically no complications. Figure 6 shows an example of the recording of an impulse at a distance of 14 m from the source, where there is an extended complication at the ascending wavefront, and no complications at the descending front. In the time interval $\Delta t = t_2 - t_1$, at all magnitudes of the amplitude, decreasing the front steepness is observed, which has a structured character. Here the complications are presented in the form of a plateau and a stress drop of a sawtooth shape. Beyond this region, the behavior of the stress profile is relatively monotonic. With increasing the amplitude, the magnitude of the sawtooth shape manifestations increases. The beginning of the stress drop occurs at point ***a***. The following drops occur at points ***b*** and ***c***. It is observed that the "micro-front" of the following, after the points ***a***, ***b***, ***c*,** stress increase has the same slope with respect to the time axis, i.e. the same steepness of the front (the dashed lines are parallel).

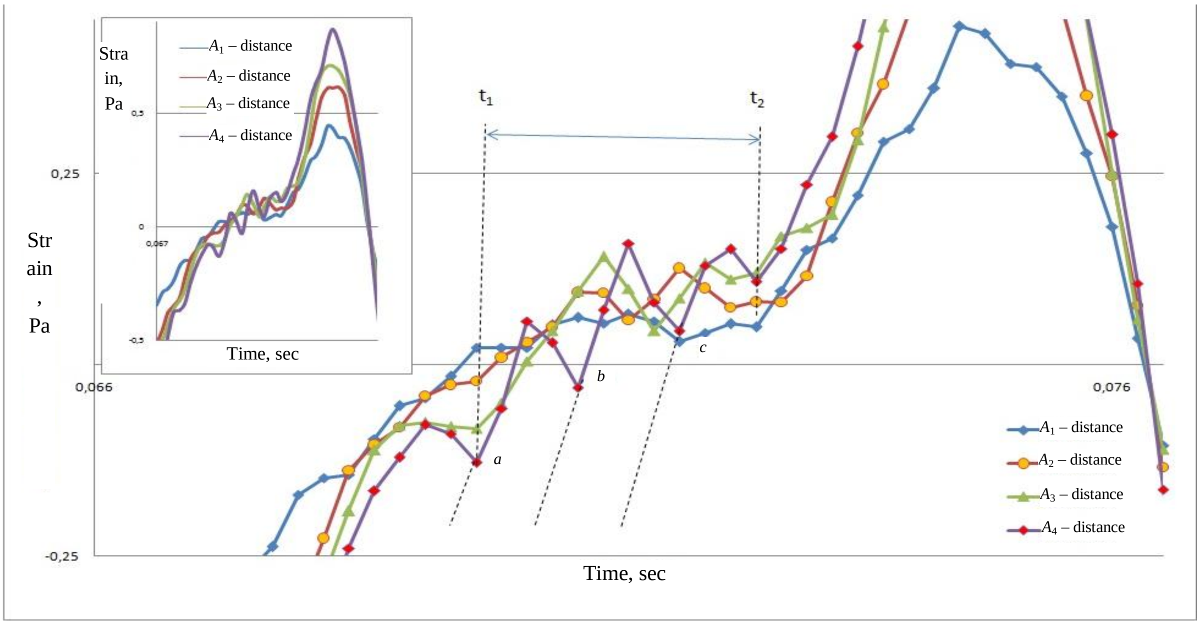

Fig. 6. Pulse records at four amplitude values recorded at a distance of 14 m from the source at a depth of 1 m

Discussion

The study of $\sigma(t)$ seismic records showed that the waveform is complicated by the inserts in the form of the plateau with boundaries marked by abrupt changes in the stress amplitude. Such an effect is supposedly attributed to the manifestation of hopping intermittent inelasticity due to rock microplasticity. Numerous data in solid state physics and materials science also indicate the mechanism of plasticity and hopping strain [1; 3; 6; 9; 14; 29; 27; 33]. It has been experimentally shown that the process of microplasticity is amplitude-dependent in nature [16, 37, 22, 25]. An intermittent change in amplitude in the form of a seismic pulse is similar to a stress stop when it reaches a critical value σ_{cr} on the curve [28]. The effective slope of the pulse front is formed with the joint participation of elasticity and inelasticity of a hopping nature. This coincides with the data obtained in material sciences. The sudden appearance of a yield plateau on the $\sigma(\varepsilon)$curves, called a sudden “displacement jump“ when loading and unloading (“pop-in” and “pop-out event”), was found in many experiments [12; 21].

Duplication of records, registration of the signal with accumulation ensures the reliability of the measurements and removes the involvement of arbitrary noise events. Repeated recording within a single time quantum does not always coincide with the first recording, as, for example, shown in Fig. 4. This is acceptable for recording with high detailing in complex material such as a rock. The effect of the same slope of the local section at the wave front after a local stress drop (Fig. 6, parallel dashed lines from points **a, b,** and **в**) was predicted in [14]. It is shown here that the sections of the stress drop in the $\sigma(\varepsilon)$ diagram are followed by the sections of elastic strain that are parallel to each other. Besides, the transition of the plateau to the stress drop (their mutual replacement), which is shown in Fig. 4, *в,* is also known. It should be noted that the ascending front of the pulse at all amplitudes has complications, while the descending front is free of them (see Fig. 6). The input pulse is always also practically “clean”.

The hopping strain and stress plateau were also found in natural materials, such as silicon [32], stishovite [30], sapphire, diorite, graphite, mica, and others [10]. Quartz grains and other minerals are present both in hard rocks and in poorly consolidated medium. Using electron microscopy, it was shown that quartz single crystals contain inclusions of various chemical composition of micrometer sizes. When a low-intensity wave propagates, quartz demonstrates signs of nonclassical inelasticity, which was recorded in the parameters of amplitude-frequency-dependent attenuation using electron microscopy [22]. It is noteworthy that the strain hopping and plateau were found in such a weak material as nanoclay [15], as well as in gypsum [13] and granite. These facts can also be regarded as an indirect confirmation of the possibility of such effects in a poorly consolidated medium. A theoretical justification of the propagation of seismic waves involving the microplasticity process was developed in [36]. It is necessary to consider other possible mechanisms, such as the acoustoplastic effect in metals and alloys [28]. In this work, experimental material was analyzed, and justifications and approaches for solving the problem of the mechanism of intermittent (hopping) inelasticity in rocks were proposed.

Conclusion

New data on the physics of seismic wave propagation in a real medium were obtained in this study. There are many mechanisms of seismic waves attenuation, however, the mechanism of intermittent (hopping) strain is not yet included in the seismic model. The new knowledge can be used to develop a rheological model and theoretical researches. It is likely that the amplitude dependence of wave velocities and attenuation is connected with intermittent inelasticity and, in particular, with microplasticity. This is evidenced by the hopping and stress-dependent nature of the strain process. The cause of waveform transformation may be microplasticity.

The problem of the nature of microplasticity in geological materials remains open so far. The mechanism of inelasticity may be the same as in solids (the motion of dislocations and other defects of the microstructure), or completely different. However, the detected manifestations of seismic microplasticity in the loams are very similar to the manifestations of microplasticity in ordinary solids. This issue needs further clarification. Microplasticity has respect to the little-known inelastic processes of propagation of low-amplitude waves in natural materials. New knowledge about elastic-inelastic processes is required not only for the theory development, but also for obtaining more effective diagnostic features for solving various applied problems by seismic and acoustic methods.

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