eISSN 2500-0632
https://mst.misis.ru/

MINING ROCK PROPERTIES. ROCK MECHANICS AND GEOPHYSICS

Research article

https://doi.org/10.17073/2500-0632-2022-1-30-36

Amplitude-initiated open hysteresis loop of *P*-wave attenuation in sandstone: experimental study

E. I. Mashinsky SC

Trofimuk Institute of Petroleum Geology and Geophysics,
Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russian Federation

✉ *MashinskiiEI@ipgg.sbras.ru*

Abstract

In the area of solid state physics and materials science, new knowledge has been attained in recent years about micro-nano-plasticity using high-precision measurements at low stresses and strain. Rock microplasticity is currently poorly understood, but in the future it may prove useful in resolving problems of a fundamental and applied nature. This study examines the effect of cyclically varying pulse amplitude and wave velocity on the attenuation parameters of longitudinal wave (P-wave) in sandstone. Laboratory measurements were performed on rock specimens using the reflected wave method in the frequency range of 0.5–1.4 MHz at five values of strain amplitude ~ (0.5-2.0)10^{-6}. Trial simulations were performed, in order to establish the effect of amplitude-dependent wave velocity on the parameters of wave attenuation in the sandstone. Wave attenuation behavior under combined action of the amplitude-dependent factor and wave velocity deviation is complex. The change in strain amplitude shifts the attenuation peak $1/Q_p(f)$ in the attenuation-frequency coordinates. The maximum change in peak attenuation value due to the amplitude factor and wave velocity deviation reaches 3–4 %. An open wave attenuation hysteresis loop was identified as a consequence of the closed amplitude cycle A1(+) --- A1(+) --- A1(–), where A1(+) = A1(–). Open attenuation hysteresis occurs both in the cases of constant and variable wave velocities. The length of the open part of the attenuation hysteresis loop relative to the peak value of the attenuation is as follows: for constant wave speed, 62.63 %, in the mode of increasing wave speed, 91.58 %; and, in the mode of decreasing wave speed, 47.01 %. The effect of open hysteresis of wave attenuation in sandstone can be explained by the action of microplastic deformation detected in the experiments.

Keywords

rock physics, amplitude-dependent wave velocity, open hysteresis of wave attenuation, microplastic strain, jump inelasticity, elastic modulus, nano-strain

Acknowledgments

I express my gratitude to B.V. Pashkov and G.V. Egorov for performing the experiments and further discussion of the results obtained.

For citation

Mashinsky E.I. Amplitude-initiated open hysteresis loop of *P*-wave attenuation in sandstone: experimental study. *Mining Science and Technology* (*Russia*). 2022;7(1):30–36. https://doi.org/10.17073/2500-0632-2022-1-30-36

СВОЙСТВА ГОРНЫХ ПОРОД. ГЕОМЕХАНИКА И ГЕОФИЗИКА

Научная статья

Амплитудно-инициируемая открытая петля гистерезиса затухания *P*-волны в песчанике: экспериментальное исследование

Э.И. Машинский SC

Институт нефтегазовой геологии и геофизики им. А.А. Трофимука,
Сибирское отделение Российской академии наук, г. Новосибирск, Российская Федерация

✉ *MashinskiiEI@ipgg.sbras.ru*

Аннотация

В физике твердого тела и материаловедении с использованием высокоточных измерений на малых напряжениях и деформациях были получены новые знания о микро-нанопластичности. В настоящее время свойство микропластичности горных пород мало изучено, но в перспективе оно может быть полезно для решения задач фундаментального и прикладного характера. В этом исследовании изучено влияние циклически изменяемой амплитуды импульса и скорости волны на параметры затухания продольной волны в песчанике. Лабораторные измерения выполнены на образцах породы методом отраженных волн в диапазоне частот 0,5–1,4 МГц на пяти значениях амплитуды деформации ~ (0,5–2,0)10^{-6}. Проведено пробное моделирование, которое дает возможность установить влияние амплитудно-зависимой скорости волны на параметры затухания волны в песчанике. Поведение затухания волны при совместном действии амплитудного фактора и девиации скорости волны имеет сложный характер. Изменение амплитуды деформации сдвигает пик затухания $1/Q_p(f)$ в координатах «затухание–частота». Максимальное изменение величины затухания в пике за счет амплитудного фактора и девиации скорости волны достигает 3–4 %. Открытая (незамкнутая) петля гистерезиса затухания волны обнаружена после действия замкнутого амплитудного цикла A1(+) --- A5(+) --- A1(−), где A1(+) = A1(−). Открытый гистерезис затухания имеет место как в случае постоянной, так и переменной скорости волны. Протяженность открытой части петли гистерезиса затухания по отношению к максимальной величине затухания составляет: для постоянной скорости волны 62,63 %, в режиме увеличения скорости волны – 91,58 % и в режиме уменьшения скорости волны – 47,01 %. Эффект незамкнутого гистерезиса затухания волны в песчанике может быть объяснен действием обнаруженной в ходе эксперимента микропластической деформации.

Ключевые слова

физика горных пород, амплитудно-зависимая скорость волны, открытый гистерезис затухания волны, микропластическая деформация, скачкообразная неупругость, упругий модуль, нанодеформация

Благодарности

Я выражаю благодарность Б.В. Пашкову и Г.В. Егорову за проведение экспериментов и дальнейшее обсуждение полученных результатов.

Для цитирования

Mashinsky E.I. Amplitude-initiated open hysteresis loop of *P*-wave attenuation in sandstone: experimental study. *Mining Science and Technology* (*Russia*). 2022;7(1):30–36. https://doi.org/10.17073/2500-0632-2022-1-30-36

Introduction and challenges

Fundamental new knowledge in physics of rock deformation can be used to improve the geological efficiency of seismic and acoustic survey methods. This requires an in-depth study of the deformation mechanism under conditions of elastic wave propagation and attenuation at the micro/nanoscale. The property of rock microplasticity, albeit exotic in geophysics, can manifest itself even at low strain. Seismic and acoustic methods use a range of low and very low dynamic strains. Dynamic processes at large and moderate strains are well understood. New knowledge about non-linearity has lead to a enhanced interest in the field of low strains in seismics [1-6].

A model has been proposed of mesoscopic elasticity to explain the mechanism of rock non-linearity. New tools, such as non-linear resonant ultrasound spectroscopy, are being used to reveal the complex behavior of rocks and other materials.

There is experimental evidence that visco-elastic-plastic models provide the most realistic representation of complex deformation in rocks when compared to traditional models. This is a significant advance in extending the range of applicability of the knowledge on inelastic processes and the prospect of practical application of the new knowledge [7, 8].

Theoretical and experimental studies in seismics and other fields of solid state physics and materials science have led to an improvement in the classical visco-elastic model of the standard linear body which describes well the dispersion, relaxation, and related inelastic processes [9–12]. The experimental findings were compared with wave velocity and attenuation predictions obtained using the Bio (jet flow) model and other models. However, these models do not take into account the effect of amplitude dependence of wave velocities and attenuation which were discovered in recent studies [13, 14]. Laboratory experiments on solid sediment samples extracted from great depths confirm the presence of amplitude effect. The behavior of dynamic parameters of seismic and acoustic waves during propagation in various media is complex and has been little studied so far.

With a change in the magnitude of the signal amplitude, both increases and decreases in the wave velocity and attenuation are observed. Decrease or increase in the elastic modulus took place in accordance with the stress-strain ratio slope of curve. Such non-standard behavior of various solids, including rock material, is caused by the joint action of elastic and microplastic deformation [15–19]. In the static stress mode, the strain amplitude effect is represented as a “stress-plateau” and “stress-descend” on the stress-strain diagram. In the dynamic mode (wave propagation), the influence of the amplitude effect can be seen in the waveform as short-term stress-plateaus and stress-descend. The microplasticity of rocks allows such an irregular short-term "inclusion" of the plasticity process with the simultaneous effect of elastic deformation which has been confirmed in theory [20, 21]. This paper presents the study results on the amplitude-dependent hysteresis of longitudinal wave attenuation in sandstone.

Research techniques and factual material

A specimen of fine-grained sandstone was prepared from a core taken from a depth of 2532 m. The sandstone density was 2.42 g/cm^3, the content of fine-grained sand fraction was 85 %, the siltstone fraction was 15 %, and the total porosity was 13 %. The experiment was conducted at a hydrostatic pressure of 20 MPa at room temperature. The cylindrical samples had the following dimensions: 40 mm in diameter; and 16 mm long. A standard three-layer model system (installation) was used in the experiment [22, 23]. The first and third layers 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 acoustic signals was provided by piezoceramic sensors at frequency of ~ 1 MHz, which were polarized to longitudinal wave. The attenuation decrement $1/Q_p$ was calculated using standard relations [24, 25]. The wave attenuation decrement was measured in a closed amplitude cycle on the ascending and descending course, where $A_{min} = A_1 \to A_2 \to ... \to A_5 = A_{max} \to ... \to A_1 = A_{min}$. In the Figures, the increase in amplitude is labeled (+) and its decrease is labeled (-). The pulse amplitude relative strain values were as follows: $\varepsilon_1 \approx 0.5 \times 10^{-6}$, $\varepsilon_2 \approx 1.0 \times 10^{-6}$, $\varepsilon_3 \approx 1.3 \times 10^{-6}$, $\varepsilon_4 \approx 1.7 \times 10^{-6}$ and $\varepsilon_5 \approx 2.0 \times 10^{-6}$. The longitudinal wave velocity in the solid sandstone was 4,330 m/sec. Increased noise immunity was provided by recording with signal accumulation.

Research Findings

The frequency dependence of *P*-wave attenuation for ascending and descending amplitude courses are shown in Figures 1 and 2 respectively. The wave attenuation at all amplitudes resembles a relaxation peak. As the signal amplitude increases, the attenuation decreases, and the peak shifts toward low frequencies, see Fig. 1. The nonlinear shift of the attenuation peak is shown by red arrows. On the descending amplitude course, the peak attenuation magnitude increases slightly, but does not return to the initial value (red arrows in Fig. 2). The amplitude dependence of longitudinal wave attenuation in sandstone at ascending and descending courses of strain amplitude is shown in Fig. 3. It represents a comparative picture of wave attenuation behavior for the three wave velocity cases. In all the cases, depending on the strain amplitude, the wave attenuation has the form of an open-type hysteresis loop. The first case took place in our experiment where the wave speed for all amplitudes was constant, 4,330 m/c. The other cases were the products of simple simulation. The second case showed a linear increase in the wave velocity at each amplitude: A1(+) = 4,350, 4,360, 4,370, 4,380, A5(+) = 4,390 m/s; and then reverse descending through the same velocity values, where(A1(−) = A1(+)). The third case showed a linear wave velocity descending from A1(−) to A5(−) (4,300, 4,290, 4,280, 4,270, 4,260 m/s) and the corresponding reverse return. The wave velocity magnitude change was linear and did not exceed the value of 0.92 %. At maximum signal amplitude, the wave attenuation decrease was as follows: for constant wave velocity, 2.83 %; for increasing wave velocity, 1.93 %; and for decreasing wave velocity, 3.77 %. At constant wave velocity, the share of the open part of the attenuation hysteresis loop is 62.63 %, at increasing wave velocity, 91.58 %, and at decreasing velocity, 47.01 %.

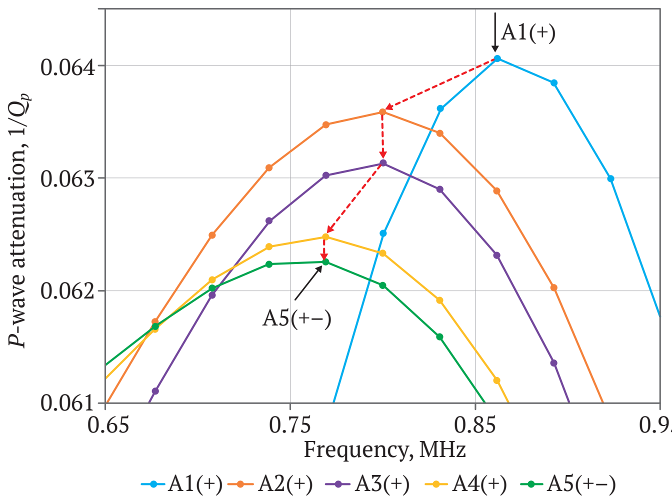

Fig. 1. Frequency dependence of the *P*-wave attenuation in sandstone at five ascending values of the strain amplitude

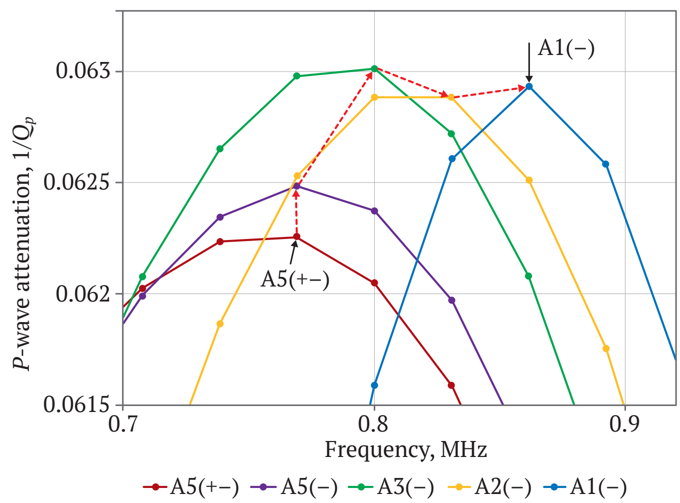

Fig. 2. Frequency dependence of *P*-wave attenuation in sandstone at five descending values of the strain amplitude

A large-scale image of fragments of the waveform at amplitudes A1(+), A1(−) and A2(+), A2(−) is shown in Fig. 4. This is the section of the wave front where the manifestations of non-standard behavior in the form of microplasticity can be seen. The Figure demonstrates the amplitude plateaus extending from one to several time quanta (tquantum), the amplitude local drop, and the effect of amplitude microhysteresis. The maximum of the wave front at amplitudes A1(+), A1(−) and A2(+), A2(−) coincide exactly in time at 31.3425 μs (red arrows in Figure 4). The lowest points on the wave front for the same two pairs of amplitudes are observed at the same time value of 31.765 μs (red dashed line in Fig. 4). At the pulse front there are local amplitude hysteresis loops of several quanta of time. Fragments of the waveform at amplitudes A3(+), A3(−), and A4(+), A4(−) are shown in Fig. 5. The signs of microplasticity described above are also present here. The peak and valley in the last phase of the pulse (31.3425 and 31.765 μs) are present at the same time as in the previous case.

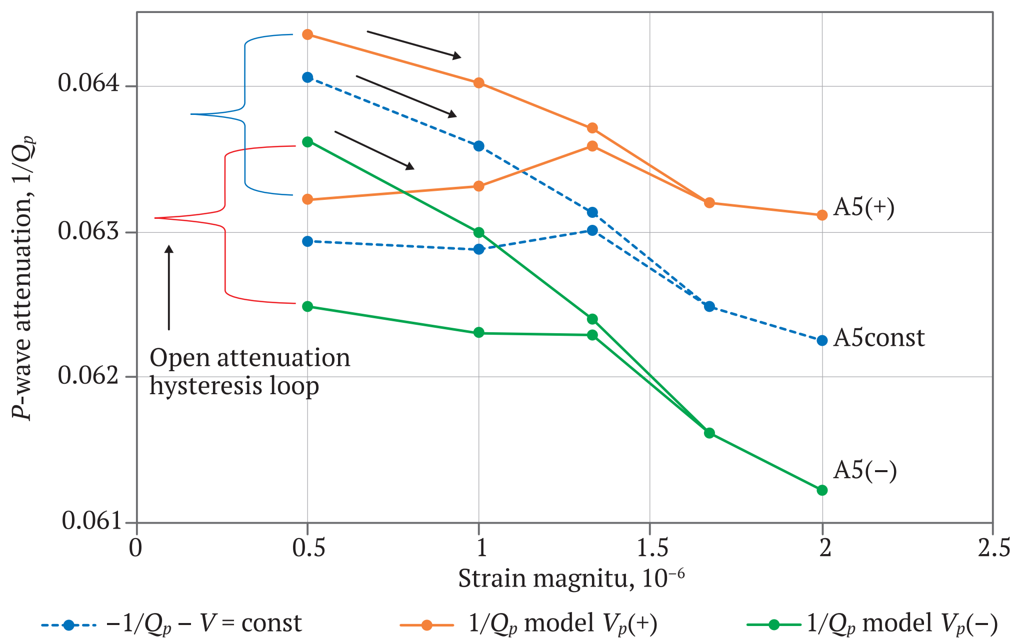

Fig. 3. Relationship between *P*-wave attenuation in sandstone and strain amplitude at the ascending and descending courses

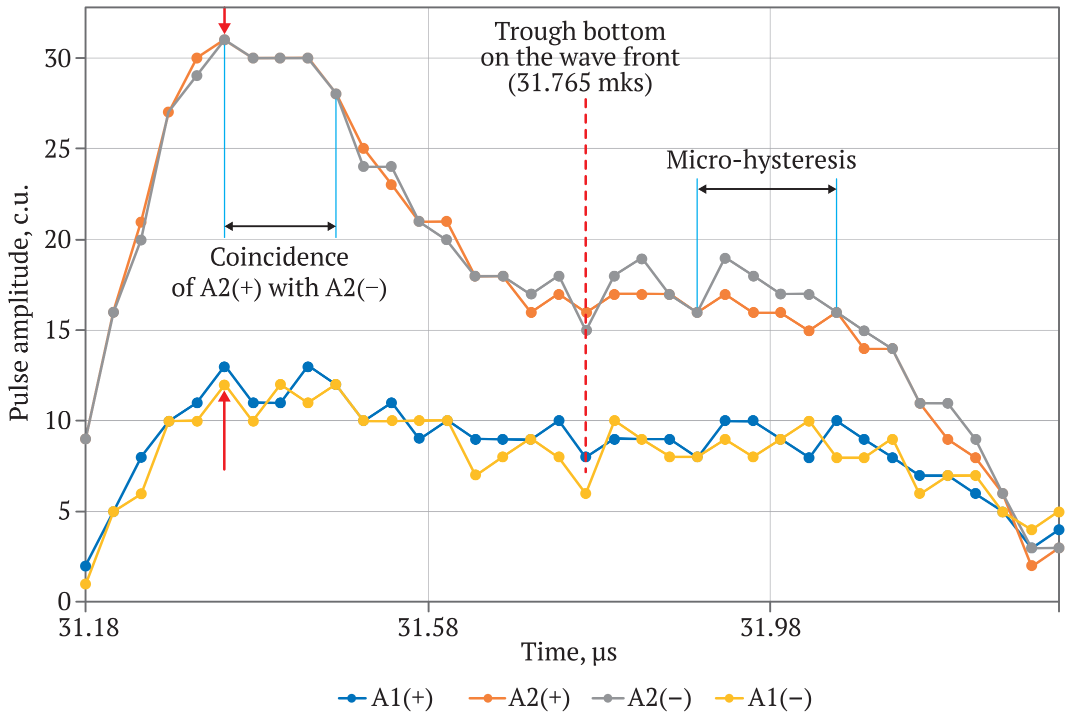

Fig. 4. Large-scale image of fragments of the waveform at amplitudes A1(+), A1(−) and A2(+), A2(−)

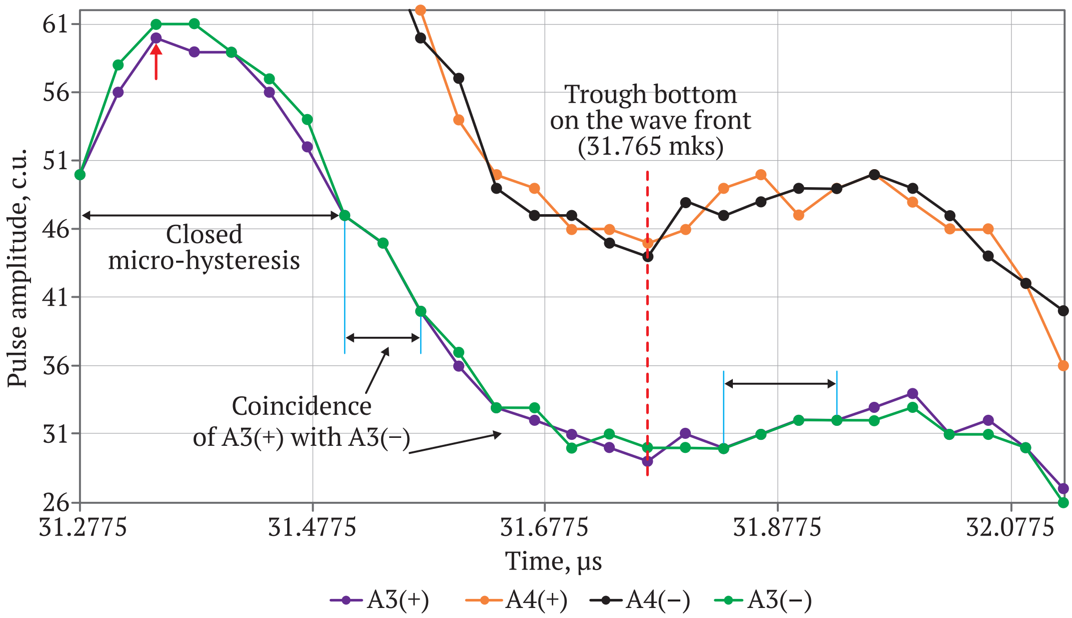

Fig. 5. Large-scale image of fragments of the waveform at amplitudes A3(+), A3(−) and A4(+), A4(−)

Discussion of Findings

The findings show that the effect of strain amplitude and wave velocity deviation on wave attenuation parameters in sandstone is unusual in character. When the amplitude value changes along the closed loop, the wave attenuation curve $1/Q_{peak}(A_{n-i})$ takes the form of open amplitude-dependent hysteresis. This requires an explanation of the deformation mechanism within the framework of rock deformation physics and solid-state physics. The open hysteresis for acoustic P-wave propagation indicates possible mechanism of non-standard inelasticity in sandstone. The most likely explanation for this effect is the mechanism of rock microplasticity. Microplastic strain depends in a complex way on the deformation leve l (the magnitude of the applied mechanical stress). The attenuation and velocity of the wave depend in a complex way on the level of dynamic deformation in the sandstone. A small change (from 0.23 to 0.9 %) in the longitudinal wave velocity in the amplitude cycle causes a greater change of 3 % in the attenuation. Novel studies conducted on rock specimens using high-precision laser Doppler interferometry showed that the change in wave velocity at the expense of amplitude reached 5 % [26, 27].

Conclusion

The experimental data analysis and the trial simulations showed the complex behavior of the wave attenuation depending on the magnitude of the amplitude and deviation of the wave velocity. In the frequency range of 0.5–1.4 MHz, wave attenuation takes the form of a relaxation peak. Changing the amplitude magnitude in a closed loop (ascending = descending) leads to shifting the attenuation peak in the "attenuation – frequency" coordinates. The maximum change in the peak attenuation value due to the amplitude factor (in the strain range of $(0.5–2.0)10^{-6}$) reaches 3 %. The combined effect of the amplitude factor and a small deviation of the wave velocity (in the range from 0.23 to 0.93 %) results in increased attenuation in the peak up to ~ 4 %. The open wave attenuation hysteresis loop detected in the experiment takes place both at constant wave velocity and at variable (amplitude-dependent) wave velocity. The relative magnitude of the open hysteresis depends significantly on the magnitude of the strain amplitude and the wave velocity deviation. The manifestations of microplasticity recorded in the experiment can be regarded as the cause of the open wave attenuation hysteresis effect in sandstone.

References

1. Gushchin V.V., Pavlenko O.V. Study of nonlinear elastic properties of rocks based on seismic data. In: *Modern Seismology, Achievements and Challenges*. Moscow; 1998. Vol. 13. (In Russ.)

2. Egorov G.V. Variations of nonlinear parameters of a consolidated porous water-saturated sample depending on the degree of gas saturation. *Fizicheskaia mezomekhanika*. 2007;10(1):107–110. (In Russ.)

3. Kondratyev O.K. *Seismic waves in Absorbing Media*. Moscow: Nedra Publ.; 1986. 176 p. (In Russ.)

4. Nikolaev A.V. *Problems of nonlinear seismic*. Moscow: Nauka Publ.; 1987. 288 p. (In Russ.)

5. McCall K.R., Guyer R.A. Equation of state and wave propagation in hysteretic nonlinear elastic materials. *Journal of Geophysical Research: Solid Earth*. 1994;99(B12):23887–23897.

6. Ostrovsky L.A., Johnson P.A. Dynamic nonlinear elasticity in geomaterials. *La Rivista del Nuovo Cimento*. 2001;24(4):1–46. https://doi.org/10.1007/BF03548898

7. Guyer R.A., Johnson P.A. Nonlinear mesoscopic elasticity: Evidence for a new class of materials. *Physics Today*. 1999;52(4):30–36. https://doi.org/10.1063/1.882648

8. Zhou Ch., Shen Zh.-J., Yin J.-H. Biot dynamic consolidation finite element analysis using a hypoplasticity model. In: *13th World Conference on Earthquake Engineering Vancouver, B.C.* August 1–6 2004. Canada; 2004. Paper No. 351. URL: https://www.iitk.ac.in/nicee/wcee/article/13_351.pdf

9. Diallo M.S., Prasad M., Appel E. Comparison between experimental results and theoretical predictions for P-wave velocity and attenuation at ultrasonic frequency. *Wave Motion*. 2003;37(1):1–16. https://doi.org/10.1016/S0165-2125(02)00018-5

10. Golovin I.S., Pavlova T.S., Golovina S.B. et al. Effect of severe plastic deformation of Fe–26 at. Al and titanium on internal friction. *Materials Science and Engineering A-structural Materials Properties Microstructure and Processing*. 2006;442(1–2):165–169. https://doi.org/10.1016/j.msea.2005.12.081

11. Sajeva A., Filograsso R., Capaccioli S. Including plastic behaviour in the Preisach-Mayergoyz space to find static and dynamic bulk moduli in granular media. In: *SEG Technical Program Expanded Abstracts*. 2018. Pp. 3517–3521. https://doi.org/10.1190/segam2018-2994837.1

12. Luoa Sh.-N., Swadenerb J.G., Ma Ch., Tschauner O. Examining crystallographic orientation dependence of hardness of silica stishovite. *Physica B: Condensed Matter*. 2007;399:138–142. https://doi.org/10.1016/j.physb.2007.06.011

13. Mashinskii E.I. Jump-like inelasticity in sandstone and its effect on the amplitude dependence of *P*-wave attenuation: An experimental study. *Wave Motion*. 2020;97:102585. https://doi.org/10.1016/j.wavemoti.2020.102585

14. Nishino Y., Kawaguchi R., Tamaoka S., Ide N. Amplitude-dependent internal friction study of fatigue deterioration in carbon fiber reinforced plastic laminates. *Materials Research*. 2018;21(2):e20170858. https://doi.org/10.1590/1980-5373-MR-2017-0858

15. Derlet P.M., Maaß R. Micro-plasticity and intermittent dislocation activity in a simplied micro structural model. *Modelling and Simulation in Materials Science and Engineering*. 2013;21(3):035007. https://doi.org/10.1088/0965-0393/21/3/035007

16. Duretz T., Souche A., Borst R., Le Pourhiet L. The benefits of using a consistent tangent operator for viscoelastoplastic computations in geodynamics. *Geochemistry, Geophysics, Geosystems*. 2018;19(12):4904–4924. https://doi.org/10.1029/2018GC007877

17. Huang J., Zhao M.,·Du X., Dai F., Ma Ch., Liu J. An elasto-plastic damage model for rocks based on a new nonlinear strength criterion. *Rock Mechanics and Rock Engineering*. 2018;51:1413–1429. https://doi.org/10.1007/s00603-018-1417-1

18. Mashinskii E.I. Difference between static and dynamic elastic moduli of rocks: Physical causes. *Russian Geology and Geophysics*. 2003:44(9):953–959. URL: https://repository.geologyscience.ru/bitstream/handle/123456789/32706/Mash_03.pdf?sequence=1&isAllowed=y

19. Mashinskii E.I. Seismo-micro-plasticity phenomenon in the rocks. *Natural Science*. 2010;2(3):155–159. https://doi.org/10.4236/ns.2010.23025

20. Vodenitcharova T., Zhang L.C. A new constitutive model for the phase transformations in monocrystalline silicon. *International Journal of Solids and Structures*. 2004;41(18–19):5411–5424. https://doi.org/10.1016/j.ijsolstr.2004.04.025

21. Liu Y., Dai F., Feng P., Xu N. Mechanical behavior of intermittent jointed rocks under random cyclic compression with different loading parameters. *Soil Dynamics and Earthquake Engineering*. 2018;113:12–24. https://doi.org/10.1016/j.soildyn.2018.05.030

22. Johnston D.H., Toksoz M.N. Thermal cracking and amplitude dependent attenuation. *Journal of Geophysical Research*. 1980;85(B2):937–942. https://doi.org/10.1029/JB085iB02p00937

23. Mashinskii E.I. Amplitude-frequency dependencies of wave attenuation in single-crystal quartz: Experimental study. *Journal of Geophysical Research: Solid Earth*. 2008;113(B11). https://doi.org/10.1029/2008JB005719

24. Jones S.M. Velocity and quality factors of sedimentary rocks at low and high effective pressures. *Geophysical Journal International*. 1995;123(3):774–780. https://doi.org/10.1111/j.1365-246X.1995.tb06889.x

25. Mavko G.M. Friction attenuation: an inherent amplitude dependence. *Journal of Geophysical Research: Solid Earth*. 1979;84(B9):4769–4775. https://doi.org/10.1029/JB084iB09p04769

26. Nourifard N., Lebedev M. Research note: the effect of strain amplitude produced by ultrasonic waves on its velocity. *Geophysical Prospecting*. 2019;67(4):715–722. https://doi.org/10.1111/1365-2478.12674

27. Nourifard N., Mashinskii E., Lebedev M. The effect of wave amplitude on S-wave velocity in porous media: an experimental study by Laser Doppler Interferometry. *Exploration Geophysics*. 2019;50(6):683–691. https://doi.org/10.1080/08123985.2019.1667228

Information about the author

Eduard I. Mashinskii – Dr. Sci. (Geol. and Min.), Trofimuk Institute of Petroleum Geology and Geophysics of Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russian Federation; Scopus ID 8886240600; e-mail: MashinskiiEI@ipgg.sbras.ru

Received 03.12.2021
Revised 20.12.2021
Accepted 01.02.2022