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On some features of ultrasound reflection water-sample in an inclined fall (physical modeling)

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In recent years, the analysis of the dependence of reflection coefficients on the magnitude of the angle of incidence of reflected waves has been successfully used in the practice of seismic research. AVO analysis (Amplitude variation with offset) is one of the methods of dynamic analysis that is used to estimate changes in the amplitude of reflected waves depending on the distance between the explosion points and the receivers. The AVO method is based on the analysis of the dependence of the reflection coefficients on the angle of incidence. In real conditions, this dependence can be determined, for example, by the roughness of the boundaries. This determines the relevance of studying the features of reflection coefficients on uneven boundaries on objects with well-controlled properties. The aim of the work is to determine the nature of the influence of different-scale roughness of seismic boundaries on the reflection coefficients of elastic waves. The work also used the technique of isolating standing waves to determine the wave velocity. As a result, graphs were obtained demonstrating the dependence of the reflection coefficients on the magnitude of the angle of incidence of reflected waves from a rough surface. Reflection coefficients were also obtained for the boundary of an isotropic medium in the direction of the isotropy plane and possible ways of applying the results were analyzed. Based on the data obtained, we can say that when the azimuth changes relative to the direction of the surface, the reflection coefficients change significantly only at the supercritical angles of incidence. *KEYWORDS:* Rough boundaries; reflection coefficients; elastic waves; physical modeling.

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Introduction

In the practice of seismic exploration in recent years, the analysis of the dependence of reflection coefficients on the magnitude of the angle of incidence of reflected waves has been used more and more successfully. One of the methods for analyzing the dependence of reflection coefficients on the magnitude of the angle of incidence of reflected waves is the AVO analysis (Amplitude variation with offset). The AVO method is based, in particular, on the analysis of the dependence of the reflection coefficients on the angle of incidence [*Jenner,* 2002; *Malehmir and Schmitt,* 2017]. Using this method, it is possible to estimate changes in the amplitudes of reflected waves depending on the distance between the explosion points and the receivers. In real conditions, this dependence can be determined not only by the ratio of the acoustic stiffness of the bordering media, but also by other factors, for example, the roughness of the boundaries.

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Rough boundaries are seismic boundaries where the size of the relief inhomogeneities is comparable to the length of the incident wave. With inhomogeneities of the surface boundary, as a result of the addition of waves diffracted by different roughness of the boundary, summarily diffracted waves are formed. Experimental research methods are often used to study the dependence of reflection coefficients on uneven boundaries, since such waves cannot be described analytically.

The reasons for the roughness of the boundaries are changes in the composition of rocks, violation of the age sequence of layers, corrugation of layers. The field of the reflected wave from such a boundary has a very complex character due to the superposition of diffracted waves.

This section of research is interesting from the point of view of studying reflection coefficients from various media, since the nature of surfaces can be controlled by physical modeling.

For example, one of the main factors determining the physical properties of fractured reservoirs, which may contain hydrocarbon deposits, in most cases is the subvertical orientation of roughness, which is due to the predominance of vertical stresses in rocks over horizontal ones. Assessment of the influence of these roughnesses and cracks on the elastic properties of rocks is one of the most important tasks of seismic exploration, which, in turn, allows us to evaluate the macroscopic properties of rocks. One of the approaches to solving this problem is physical modeling with the creation of various artificial samples [*Dugarov et al.,* 2020].

This work is also of value for engineering seismology. In the construction of buildings and structures, both frequency and amplitude distributions are of great importance. Most often, attention is paid to the frequency distribution, while the amplitude distribution has not been fully studied. However, the reflection of amplitudes is an important part in construction, since the amplitude of natural oscillations increases with the height of the building [*Standard,* 2017].

Currently, there are not many publications on the study of reflection coefficients from rough edges. In Russia, most of the publications were carried out by K. V. Fedin and Yu. I. Kolesnikov. In their works, they considered waves reflected from azimuthally anisotropic surfaces [*Kolesnikov et al.,* 2018] and uneven media interfaces. Despite the different nature of the surfaces, both works give similar results. In order to refute or verify the random regularity of the results of previously conducted experiments, we chose a rough surface model with well-controlled properties that differed from the studied samples. Based on the results of the experiments given in this article, it can be said that the effect of the roughness of the boundaries on the reflection coefficients depends on the characteristics of the surface and the wavelength, so it cannot be said that the reflection coefficients are universal for all surfaces.

Materials and Methods

The purpose of this work is to determine the nature of the influence of different-scale roughness of seismic boundaries on the reflection coefficients of elastic waves. To achieve this goal, we have identified the following tasks:

1. Conduct a physical simulation of elastic waves reflected from the boundary of water and a rough model;
2. To obtain a good correspondence of the calculated and experimental reflection coefficients;
3. Analyze previously published works on similar topics and, based on the results obtained, draw conclusions about whether they are random or natural.

We selected the sample sizes ($10 \times 10 \times 2$ cm^3) that would be convenient for its use. Plexiglass was used as the material [*Karaev et al.,* 2008]. The sample modeling a rough surface with a triangular profile (height 19.1 mm, width 102 mm, segment size 0.33 mm) was made on a CNC machine (numerically controlled) [*Fedin et al.,* 2020; *Zeltmann et al.,* 2016]. Figure 1 shows the sample itself (a) and its structure (b).

The velocity was also measured by the standing wave method. Such waves can occur when traveling waves are reflected from obstacles. For such waves, the values of the period, amplitude and polarization are the same. In this case, depending on the reflection conditions, both the opposite node (for example, if the sound is reflected from its air boundary in water) and the vibration node (if it is reflected from the same sound boundary in air) are located on the reflecting boundary. It is known that standing waves with equal frequencies can form in

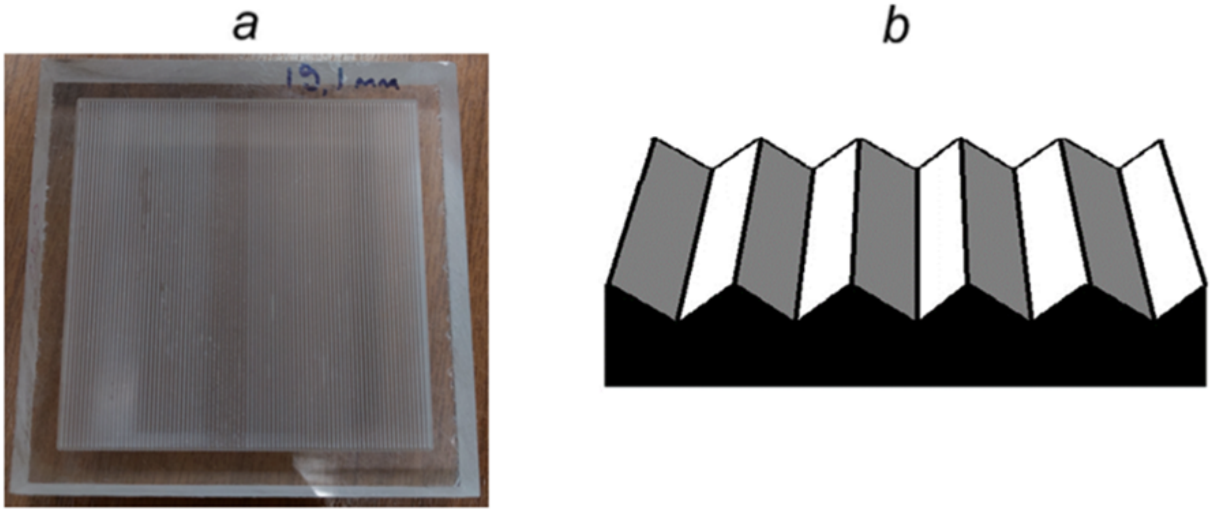

Figure 1. (a) A sample made on a CNC machine; (b) sample structure.

closed bodies, in this case a family of compression-expansion waves is formed [*Dugarov et al.,* 2020]. That is, nodes of standing waves are formed at boundaries that are equal to half the wavelength. In our experiment, the velocity in plexiglass measured by the standing wave method was 2790 m/s.

The propagation velocity of interfering waves is equal to:

$$V = \frac{2Hf_n}{n}.$$

Here f_n – the natural frequencies of the object, H – distance between borders, n – standing wave mode number.

For the reliability of the result, we also measured the velocity using an acoustic (both pulsed and complexing with a resonant method) method [*Červený and Ravindra,* 1971]. Both of these approaches gave the same results of the longitudinal wave velocity in the sample of 2790 m/s.

The schematic diagram of the experiment is shown in Figure 2a.

A lever device was used to determine the reflection coefficients and change the angles of incidence α (Figure 2b).

When the sample was rotated clockwise around an imaginary vertical axis, the azimuth β changed relative to the isotropy plane (Figure 2c) [*Chang et al.,* 1995].

The lever device made it possible to rotate the source and receiver (hereinafter referred to as sensors) of ultrasonic pulses independently of each other. The sensors themselves have always been oriented perpendicular to the axis of rotation of the levers.

The position of the source and receiver remained unchanged, which prevented the divergence of angles. When changing the angle of incidence in increments of 2° (starting from 5°), the position of the reflection center was in one place.

The measuring equipment is made of thin-layer piezoceramic. The source and receiver are at equal distances. Thus, the beam length has always been constant (13.5 cm). During the registration of reflections, when the angle increase, a straight wave occurs. A styrofoam plate located between the sensors was used to shield it. During the experiment, the design was constantly in the water with the control of the sample position.

In order to verify the correctness of the data obtained and to compensate for the influence of geometric dispersion on the measurement results, measurements of straight waves with fully open arms without a sample were carried out at the beginning and at the end of the experiments. A rectangular electric pulse with a duration of 1×10^{-6} s with a repetition frequency of 2.65 Hz and an amplitude of no more than 60 V was applied to the source. Ultrasonic pulses were recorded on a computer using a BORDO-423 digital oscilloscope, amplified and converted by the receiver into electrical signals. Experimentally, it was determined that a 100-fold accumulation of signals minimizes noise (signal-to-noise ratio).

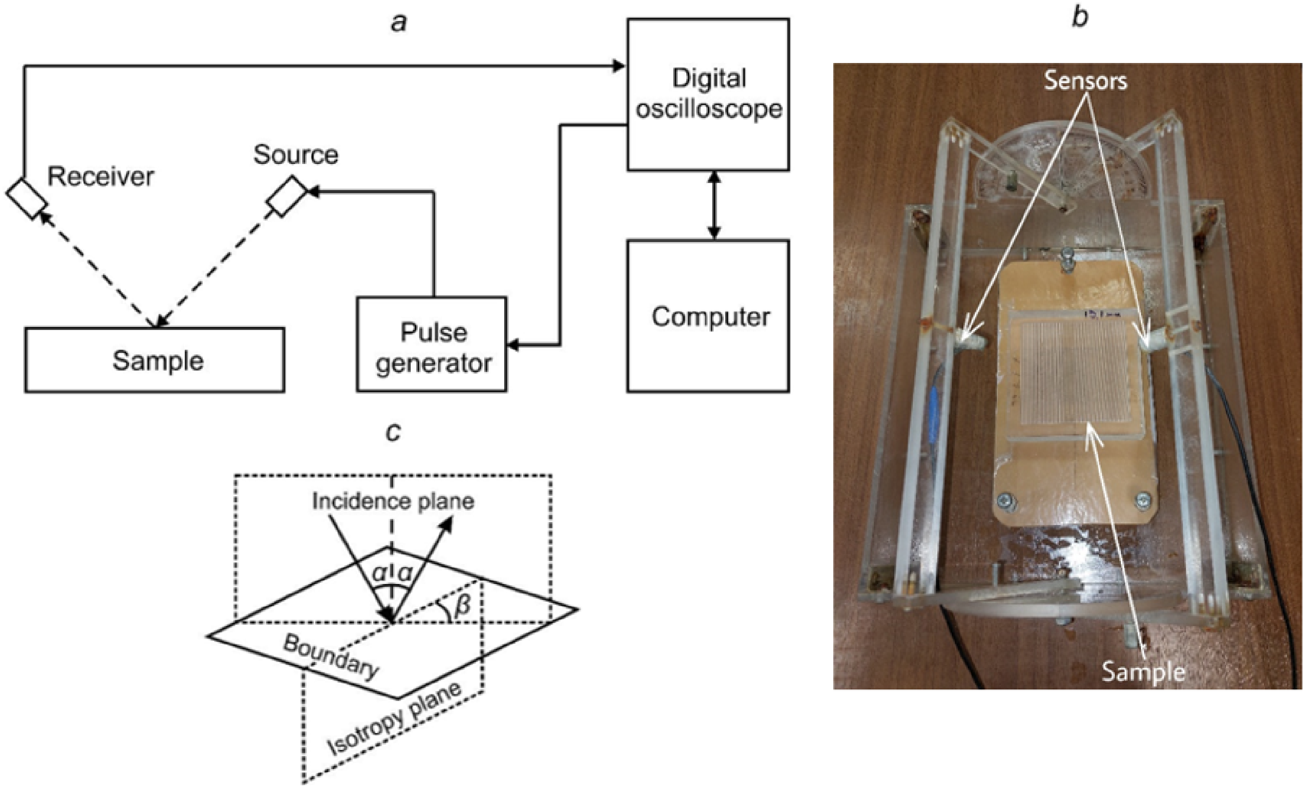

Figure 2. (a) Schematic diagram of the experiment; (b) lever device design; (c) determination of the angle of incidence α and azimuth β.

During data processing, the amplitude of the reflected signal is measured for each angle of incidence for the same time interval.

To calculate the reflection coefficient modules, the formula was used:

$$|k| = \frac{H^r_{\max} - H^r_{\min}}{H^d_{\max} - H^d_{\min}}$$

Here $H^r_{\max}$ and $H^r_{\min}$ – maximum and minimum amplitudes of the reflected wave; $H^d_{\max}$ and $H^d_{\min}$ – the maximum and minimum amplitudes of the forward wave.

Earlier [*Kolesnikov,* 2005] experiments were carried out to study ultrasonic pulses from the boundary of water with not perfectly elastic media in the case of an inclined fall. Using the example of "water-plexiglass", where plexiglass plays the role of most crystalline rocks with weak absorbing properties, it was found that the reflection coefficients are satisfactorily described by formulas obtained for ideally elastic media (Figure 3a). Repeating this experiment with a larger range of angles of incidence and a smaller step, we obtained an experimental curve that also corresponds well to the theoretical curve (Figure 3b).

Results

The dependences of the reflection coefficient modulus on the angles of incidence on a rough surface are obtained for azimuths from 0° (across the roughness) to 90° (along the roughness) (Figure 4a). All measurements were carried out in the range from 5° to 90° with a step of rotation of the angle of incidence of 2°. For clarity, Figure 4b shows graphs of the sample position across and along the roughness (azimuth 0° and 90°, respectively).

As you can see, the reflection coefficient modulus for different azimuths has similarities. But at large angles, the dependence of this parameter is different. It has maximum values at angles of incidence close to 37–45° and 90°.

Based on the total values for all azimuths and angles of incidence studied, we constructed a surface (Figure 5).

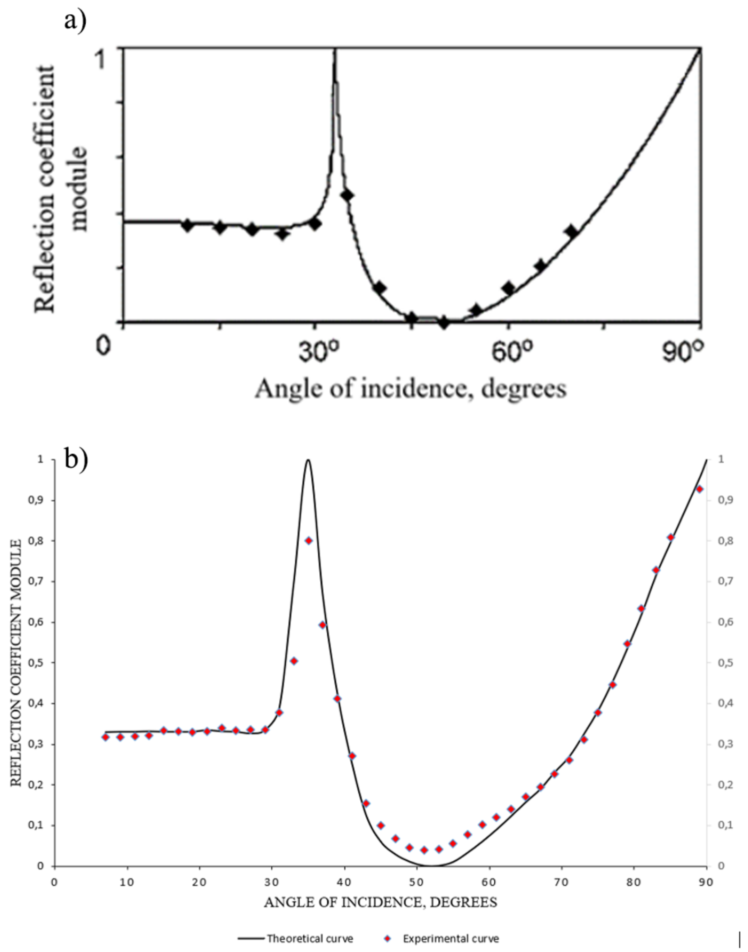

Figure 3. (a) Experimental (individual points) and theoretical dependences for the case of ideal elasticity (solid line) [*Kolesnikov,* 2005]; (b) experimental and theoretical dependences of the reflection coefficient modulus on the angle of incidence for the “water-plexiglass” boundary.

On the resulting surface, it is clearly visible that at a small angle of incidence, the modulus of the reflection coefficient practically does not depend on the azimuth. However, with a large angle of incidence, there is a strong dependence of the reflection coefficient on the angle of incidence.

Discussions

To analyze the results obtained, it is interesting to compare them with the results of experiments given in a number of other articles. In these works, the reflection of elastic waves from the boundaries with anisotropic media was studied, as well as with the article [*Kolesnikov,* 2005; *Kolesnikov et al.,* 2018], in which the dependence of reflection coefficients on the roughness of the interface of media was investigated. All of the above experiments are united by the weak dependence of the reflection coefficient modules on different azimuths at small angles of incidence.

Note that for the angle of incidence studied, the range from 25° to 35° corresponds to the critical angle. Since the main changes occurred precisely in the area of critical angles, where the reflection coefficients are maximum, the approximate coincidence of the angles (25–35°) is probably not accidental. However, based on the results of the experiment, we cannot say whether this angle depends on the parameters of the uneven boundaries.

Due to the difference in critical angles for different azimuths, this dependence of the reflection coefficients manifests itself in the form of changes

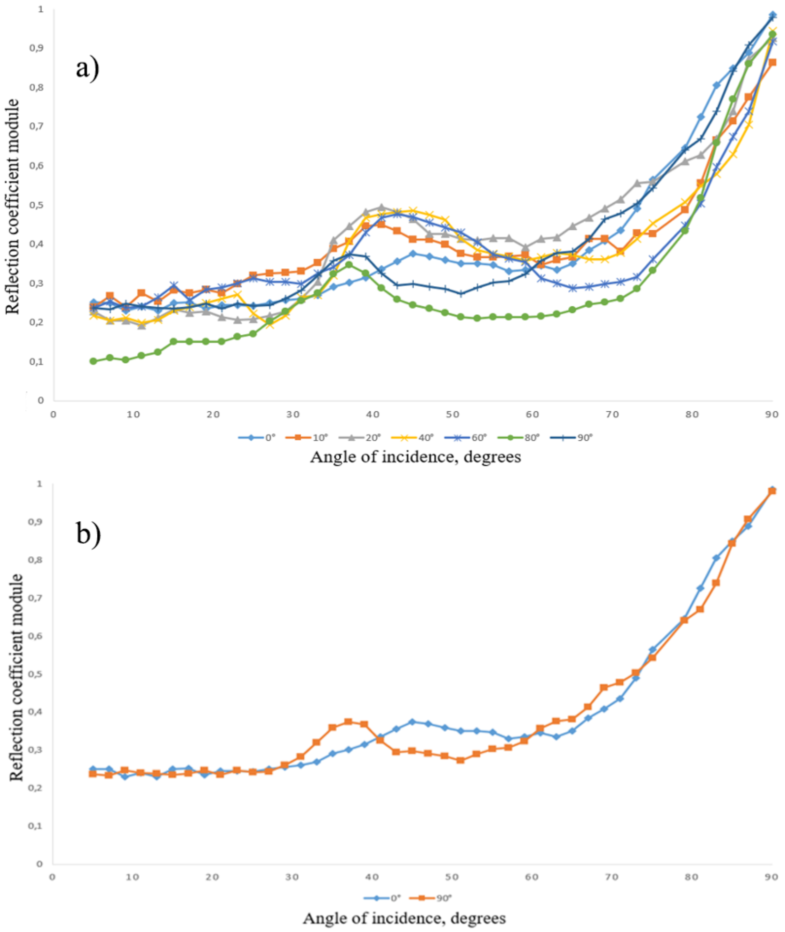

Figure 4. (a) The dependencies of the reflection coefficient modules on the angle of incidence on a rough surface. The color shows the different azimuth values. (b) Graphs of the dependence of the modulus of reflection coefficients on the angle of incidence. The color shows the values for azimuths 0° (across the roughness) and 90° (along the roughness).

only in those angles of incidence at which these maxima are observed.

In our experiment, the values of the reflection coefficients for angles of incidence less than 33° were very close, while the reflection coefficients for angles of incidence more than 33° increase significantly.

According to previously published articles [*Kolesnikov,* 2005; *Kolesnikov et al.,* 2018], it can be assumed that there should be such a dependence. At the same time, in the case of a high-speed anisotropic medium, the absence of azimuthal dependence of reflection coefficients in the range of subcritical angles was noted. However, for different reflective media, the critical angles can vary greatly. Consequently, the “cut-off angle” of 25–30° observed in the two experiments mentioned above cannot be considered a universal characteristic. It can take different values for different environments.

Since one conducted experiment does not allow us to draw serious conclusions about the universality of the obtained coefficients, then, taking into account the experience of other authors, we can say that for each rough boundary there are their own characteristics and their peak values. Only the values at subcritical angles remain common, and the azimuth change significantly affects the reflection coefficients only at subcritical angles.

It is known that reflection from an inhomogeneous boundary occurs in the same way as in the case of isotropic media with the velocities of

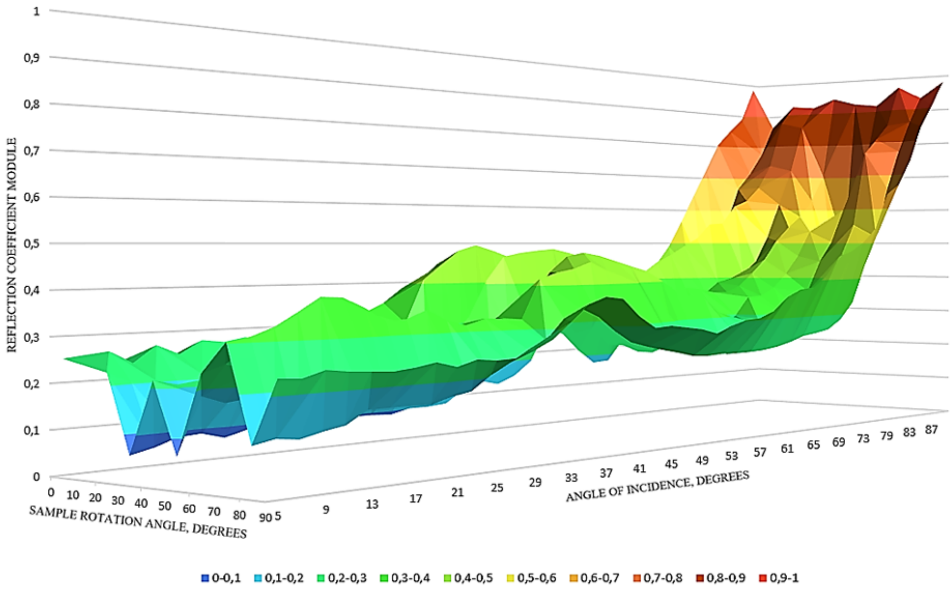

Figure 5. The dependence of the reflection coefficients on the angle of incidence and azimuth of the point of incidence relative to the roughness position. (The range of values of reflection coefficients is indicated by color).

the corresponding waves, provided that the shear waves/the compressions are polarized in the same plane [*Mallick et al.,* 1998; *Rüger,* 1997].

The velocity in plexiglass measured by the standing wave method was 2790 m/s. Since the distance from the sources is many times greater than the wavelength, the waves can be considered almost flat [*Aki and Richards,* 1980].

It should be noted that at higher azimuthal angles (for example, 80), the average values of the experimental reflection coefficients are slightly lower than at other angles. It can be assumed that these deviations are associated with a large angle of rotation and the inhomogeneity of the rough surface of the sample, which varies depending on the angle of rotation. It is also likely that the deviations may be related to changes in water temperature.

Conclusions

In this paper, using the example of a sample modeling a rough surface, we have shown the dependence of the reflection coefficients on different angles of rotation of the rough boundary.

According to experimental data, we found out that the reflection of elastic waves from a rough surface in a rather complicated way depends on the azimuth. At small values of the angles of incidence (up to 33°), the azimuthal dependence is weakly observed. However, depending on the azimuth of the plane of incidence, at large angles of incidence, the value of the reflection coefficient modulus can vary significantly both up and down.

The reflection coefficients are not constant over the entire surface, as they are affected by the roughness of the boundaries depending on the characteristics of the surface and the wavelength. If the size of the roughness is constant, the azimuth increases, then the reflection coefficients at subcritical angles decrease and increase at supercritical angles of incidence.

All of the above features of the dependence of the reflection coefficients on the azimuth of the plane of incidence can be widely used in practice, for example, to determine the direction of the preferred orientation of cracks in flooded reservoirs.

At the moment, research in the direction of studying reflection coefficients from various media has not been fully studied, so it is of interest to continue research in this direction for other interfaces boundary.

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References

Aki, K., P. Richards (1980), *Quantitative Seismology, Theory and Methods (2nd edn. Vol. 1)*, 557 pp. Freeman, San Francisco.

Červený, V., R. Ravindra (1971), *Theory of Seismic Head Waves*, 312 pp. University of Toronto Press, Toronto. **Crossref**

Chang, C. H., G. H. F. Gardner, J. A. McDonald (1995), Experimental observation of surface wave propagation for a transversely isotropic medium, *Geophysics*, *60,* 185–190, **Crossref**

Dugarov, G. A., Yu. I. Kolesnikov, et al. (2020), Acoustic measurements on artificial fractured samples made using FDM 3D printing technology, *Proceedings of the All-Russian Acoustic Conference (St. Petersburg, 2020)* p. 621–626, POLYTECH-PRESS, SPb. **Crossref**

Fedin, K. V., Y. I. Kolesnikov, et al. (2020), Research of reflection of elastic waves from rough borders (physical modeling), *Processes in GeoMedia*, *23,* 634. (In Russian)

Jenner, E. (2002), Azimuthal AVO: Methodology and data examples, *The Leading Edge*, *21,* 782–786, **Crossref**

Karaev, N. A., Yu. P. Lukashin, et al. (2008), Physics modeling of a fractured media, *Seismic Technologies*, *2,* 64–73.

Kolesnikov, Y. I. (2005), Reflection of ultrasonic pulses from the interface between water and nonperfectly elastic media: experimental data for the case of oblique incidence, *Phys. Mesomech.*, *8,* 43–48. (In Russian)

Kolesnikov, Yu. I., K. V. Fedin, Yu. A. Orlov (2018), Physical modeling of reflection of elastic waves from an azimuthally anisotropic medium, *Sb. mater. XIV International Scientific Congress. "Subsurface use. Mining. Directions and technologies of prospecting, exploration and development of mineral deposits. Economy. Geoecology" (in 6 vols., Vol. 3)* p. 3191–3198, SGUGiT, Novosibirsk.

Malehmir, R., D. R. Schmitt (2017), Acoustic reflectivity from variously oriented orthorhombic media: analogies to seismic responses from a fractured anisotropic crust, *Journal of Geophysical Research – Solid Earth*, *122,* No. 12, 10,069–10,085, **Crossref**

Mallick, S., K. L. Craft, et al. (1998), Determination of the principal directions of azimuthal anisotropy from P-wave seismic data, *Geophysics*, *63,* 692–706, **Crossref**

Rüger, A. (1997), P-wave reflection coefficients for transversely isotropic models with vertical and horizontal axis of symmetry, *Geophysics*, *62,* 713–722, **Crossref**

Standard (2017), *State Standard 34081-2017. Buildings and constructions. Determination of parameters of the basic tone of natural oscillations*, 19 pp. Standartinform, Moscow. (In Russian)

Zeltmann, S. E., N. Gupta, et al. (2016), Manufacturing and Security Challenges in 3D Printing, *JOM*, *68,* 1872–1881, **Crossref**

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