

Shallow seismic sounding based on ellipticity analysis of microtremor

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Abstract. A brief review is carried out of the previous study about the spectral ratios of horizontal and vertical components of microseismic oscillations displacement. The basic principles of resonant boundaries allocation and the construction of deep sections based on the H/V relations (ellipticity) are considered. A description of the equipment used, the method of recording and processing microseismic noise are presented. The main goal of the research work is to clarify the nature of the connection between the ellipticity of microseisms with geological features and the correctness of constructing deep sections based on them. The initial data are the amplitude spectra of the components of microseismic signal, obtained using the fast Fourier transformation. In the course of experimental work it was found that the spectral relations retain their characteristic features regardless of the azimuth of observations. A number of practical examples compare microseismic sections with results from other geophysical methods and drilling information. The results obtained indicate the complex nature of the ellipticity of microseismic noise under different conditions, however, they make it possible to determine the main interfaces between the upper part of the geological section. Resonant boundaries emitted by microtremor are often located near refractive seismic boundaries. This is consistent with the theory that resonance effects occur at the interface between two media with a high contrast of acoustic impedance.

Keywords: microtremor, H/V-ratio, Nakamura's technique, resonant boundaries, deep section, microseismic sounding

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Introduction

The possibility of using microseismic noise to study the deep structure of the Earth has long been occupied by the minds of scientists. Studies carried out in this direction led to the accumulation of numerous materials indicating the correlation of the spectral characteristics of microseisms with various geological objects and structures. On the basis of the data obtained in our country, such methods of geological study using passive seismicity, such as the method of microseismic sounding (MSM) (Gorbatikov et al., 2008), ANCHAR (Graphov et al., 1996), low-frequency seismic sounding (Berezhnoy et al., 2008) and others.

Similar works were intensively carried out abroad. As early as the middle of the 20th century, seismologists assumed that the ratios of the radial and vertical components of particle motion functionally depend on the parameters of the underlying layer: thickness, density, and velocity of seismic waves (Boore, Toksoz, 1969). To study these functional dependencies, "new" technologies

for that time were used – spectral analysis of seismic vibrations in different modifications for longitudinal (P), transverse (S) and surface waves (Bath, 1974). However, these studies did not receive wide development due to the complexity of calculations and the ambiguity of results. The method, based on estimating relationship between amplitude spectra of the horizontal (H) and vertical (V) components of microseismic vibrations, was originally proposed by Japanese seismologists Nogoshi and Igarashi (Nogoshi, Igarashi, 1971). Interest in further studying this issue appeared after an article by their colleague Nakamura (Nakamura, 1989), in which he showed that the H/V ratios of the amplitude spectra of microseisms have a relationship with the dynamic characteristics of the geological section. After this publication, all technologies using H/V spectral ratios became known as the Nakamura method. Despite numerous works in this direction (Fäh, 2001; Narayan, 2002; Parolai, Galiana-Merino, 2006), among geophysicists there is still no common opinion and complete clarity on this issue. The explanation of the nature of the H/V relations adopted by most researchers is formulated as follows:

- microseismic noise mainly consists of surface waves (thus, the vertical component mainly corresponds to the Rayleigh wave);
- the ellipticity (H/V ratio) of the Rayleigh waves changes with a frequency f corresponding to certain depths of research h ;
- in a homogeneous isotropic medium there is a proportional dependence of the ellipticity of Rayleigh waves on the Poisson's ratio;
- in the contact area of two geological layers that are more than 2.5 times different in acoustic rigidity (impedance), transverse wave resonance occurs with a maximum peak at a frequency (Nakamura, 2000; Chatelain et al., 2008):

$$f_0 = V_S / 4h_0$$

where V_S is the velocity of transverse waves in the upper horizon; h_0 is the depth of contact of the layers.

This is consistent with theoretical calculations of the behavior of Rayleigh waves in a two-layer medium (Malischewsky, Scherbaum, 2004). The velocity of the transverse waves in the upper layer can be determined from the propagation velocity of the Rayleigh wave V_R , taking into account the Poisson's ratio of the medium (μ) – $V_S = (1 + \mu) \times V_R / (0.87 + 1.12\mu)$ (Puzyrev et al., 1985). For most rocks (при $\mu = 0.25 \div 0.5$) this ratio corresponds to $V_S = 1.05 \div 1.09 \times V_R$.

Thus, it is possible to determine the depth of the resonant boundary by the formula:

$$h_0 = V_S / 4f_0 \approx 1.07 \times V_R / 4f_0$$

where f_0 is the frequency of resonant oscillations of transverse waves.

In the case of a standard two-layer section consisting of a surface layer of "loose" soil and a solid base (bedrock), one resonant peak should be present in the spectrum of the H/V relationship, from which it is possible to determine the depth of the main geological boundary. In homogeneous space, resonance phenomena are absent, and then sections of spectral ratios characterize changes in the acoustic properties of the medium. In an inhomogeneous layered medium, a total interference pattern will be observed, depending on the elastic parameters of individual elements of the medium, boundary resonance effects and the influence of various wave modes. In addition, spectral relationships are influenced by the nature of main sources of microseismic noise, on which the dominance degree of Rayleigh waves in the overall seismic response depends (Haghshenas et al., 2008). When studying the upper part of the section in the range of technogenic microseismic noise ($f \geq 1$ Hz), despite the many influencing factors, the spectral relations have a rather simple form. Typically, the number of resonant peaks does not exceed two, so the H/V ratio allows selecting only the most contrasting structural elements of the geological structure. For a

visual representation, the results of soundings can be presented in the form of amplitude spectra of $|H/V|(f)$, or spectrograms along a profile of observations similar to frequency pseudo-sections. However, the use of the microseism elliptic cuts transformed into the depth range is more obvious by the formula:

$$h \approx 1.07 \times V_R / 4f$$

Then the boundaries of sections can be identified by the depth and shape of occurrence in the form of linear anomalies of elevated (peak) values of the H/V ratios. These boundaries should be called resonant. To calculate the depth of their occurrence, it is necessary to determine the average velocity of Rayleigh waves in the overlying stratum. For a simple two-layer cut, this is straightforward, but in a multilayer medium the velocity of the surface waves depends on the oscillation frequency. To take into account changes in the phase velocities of Rayleigh waves, we can use one of the dispersion analysis methods: SASW (Spectral Analysis of Surface Waves) (Heisey et al., 1982), ReMi (Refraction Microtremor – refraction of microseisms) (Louie, 2001), or MASW (Multichannel Analysis of Surface Waves) (Park et al., 2007). At the same time, to fix the depth, it is enough to obtain the frequency response $V_R(f)$ in several of the most characteristic places of the profile, using the average approximation dependence for the other points. After calculating and making corrections for the velocity dispersion of Rayleigh waves, we obtain more accurate positions of the resonant boundaries in a multilayer section.

The purpose of this work is to study the ellipticity of microseismic vibrations to determine the correctness of constructing deep sections based on them, under various geological conditions and depths of the boundaries of the sections. The main objectives of the research are the comparison of microseismic sections obtained with geological data and the results of other geophysical methods.

Method of works

Field observations of microseisms were conducted in the Middle and Polar Urals in the 1-1000 Hz frequency range. This range allows exploring only the upper part of geological section, so these works should be characterized as shallow seismic sounding. Sometimes we will use a more general name – microseismic sensing. The registration of the microseismic background was carried out using an autonomous seismic station based on a universal geophysical receiver of the OMAR-2 series (Davydov, 2016a). Low-frequency vertical and horizontal seismic receivers of Geospace Technologies, fixed in one package, were used as sensors. Due to the circuitry correction, a linear amplitude-frequency characteristic of the seismic path has been achieved in the entire range of frequencies used. The optimal

signal gain was set immediately before starting work on the recording level indicators. Using the SpectraLAB program (Sound Technology Inc., USA), real-time fast Fourier transformation (FFT) of the V/H ratios was performed in the continuous averaging mode of sequentially calculated spectra, displayed on a laptop screen for monitoring. The sampling rate was 4 kHz, the size of the FFT data block was 8192 points, which smoothed the Hanning window. Experimental studies of the shape of the obtained spectra at different recording durations (up to one hour) showed that the spectral relationships ceased to change significantly after two or three minutes of recording with accumulation. Standard observations were performed by continuous two-channel recording of microseismic noise for 3 to 15 minutes at each point. A longer recording time was used to allow the rejection of impulse noise from nearby man-made sources during post-processing. Information in real time passed analog-to-digital conversion and stored in flash memory (SD card) of a digital recorder or laptop as files in pulse code modulation. At the end of the field work, the time series records were copied, edited and processed in-house conditions using a special software package. The main information material was the amplitude spectra of the components of the microseismic signal and their relations, obtained using the fast Fourier transformation (Fig. 1).

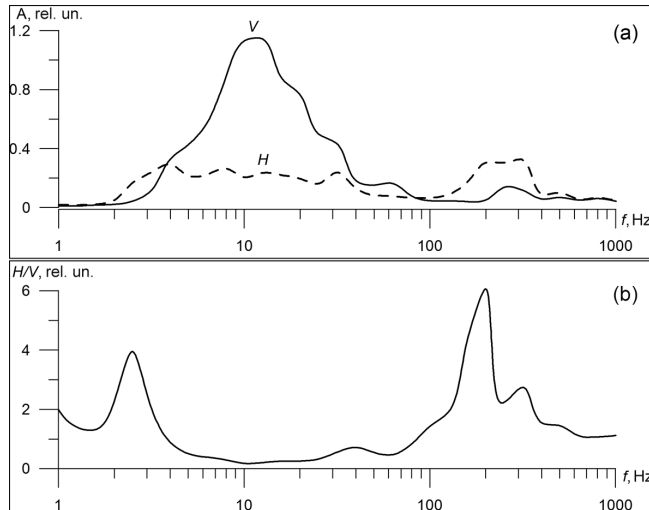


Fig. 1. Amplitude spectra of microseismic oscillations: a) horizontal (H) and vertical (V) signal components; b) H/V -ratio (ellipticity).

To visualize the final results, spectral relations were transferred from the frequency domain to the depth range, taking into account the velocity dispersion of the fundamental Rayleigh wave mode. Experimental and methodical work on the study of microseisms was usually accompanied by complex geophysical work, or carried out in places where such work was done earlier. Therefore, the dispersion of the Rayleigh wave

velocities was taken into account based on the available shallow seismic survey data. The main method of seismic research was the method of refracted waves (MRW), the end result of which is to obtain high-speed seismic sections of longitudinal waves and determine the configuration of refracting boundaries. Seismic exploration was carried out using a Sinus-24M portable digital seismic station (Senin, Senina, 2005) according to the previously developed method of combined observations MRW and MASW (Davydov, 2010), using a system of oncoming and catching hodographs. Other types of geophysical studies were carried out according to standard methods, in accordance with the recommendations and instructions for the relevant types of work.

The analysis of the obtained microseismic elliptic sections was carried out by comparing them with geological data, as well as with the results of geophysical works, mainly seismic ones. Further the main features of deep microseismic sections, constructed using spectral ratios, are considered with specific examples.

Research results

With a uniform distribution of single sources of microseisms in a homogeneous medium, the horizontal oscillations in any direction are statistically equivalent. In real environments, the distribution density of microseismic noise sources is uneven, and there are local scattering inhomogeneities of the medium. To simplify the observation technology, it is necessary to solve the problem of how strongly the spectral ratio sections differ when the azimuth of the horizontal component changes. In order to find out, experimental-methodical work was carried out on a number of different geological objects. In the course of the work, it turned out that in most cases only the amplitudes of the horizontal components change, while the shape of the spectrum itself remains relatively stable. Those sections of the spectral relations retain their main characteristics, regardless of the azimuth of the horizontal component of the signal. This is demonstrated by the results presented below, obtained on the Novoalekseevsky array (Fig. 2).

At the base of the section, gabbro and gabbro-diorites overlapped with lake-marsh sediments are deposited. According to the seismic survey data, the refractive boundary corresponding to the top of the bedrock is horizontally located at a depth of about 8 meters. The obtained images of the resonant boundaries at different azimuths of the horizontal seismic receiver installation differ from each other in details, but correspond to the same depth. The absolute amplitude of horizontal oscillations corresponds to the geometric sum of two orthogonal components in the horizontal plane. When using one horizontal seismometer, it must be installed in the direction of the main sources of microseismic

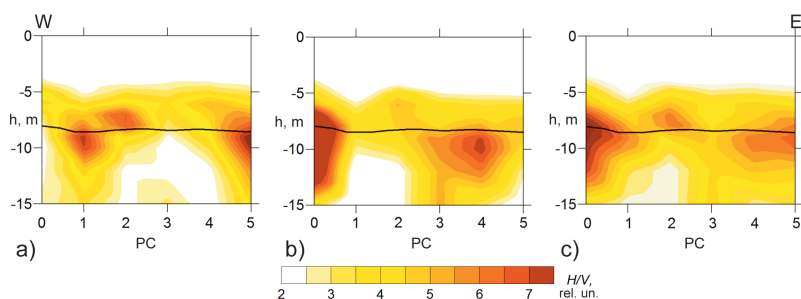


Fig. 2. Cuts of microseism ellipticity at different azimuths of horizontal seismic receiver installation: a) H_x/V relations cut in the latitudinal direction; b) H_y/V relations cut in the meridional direction; c) total cut of H/V relations. The solid black line shows the refracting border. Pickett (Pc) numbering is a multiple of 10 meters.

noise (roads, ponds, trees, etc.), then the measured component will be closest to the absolute value. The figures presented show that all horizontal resonant interfaces look more chaotic than the seismic refracting border. The result may indicate the influence of other physicomaterial parameters of the medium and the contact area under specific conditions of the occurrence of soils. In this case, the fluctuations of the resonance boundary may be related to the velocity inhomogeneities of the overburden, which include peat lenses. The microseismic sections obtained also indicate that there may be a resonance of seismic waves in the vertical plane. This effect is discussed in more detail at the end of the paper.

In the absence of contrasting horizontal boundaries, resonance phenomena should not occur. On some of the Ural arrays we studied, the resonance peaks of the ellipticity of the microseisms either did not appear at all or were very rarely observed (Davydov, 2015). This is explained by the rather homogeneous composition of the source rocks and the formations covering them. Most often, this situation is characteristic of intrusive arrays confined to elevations and covered with low-thickness, slightly modified weathering crust. The transition of source rocks to weathering crust rocks can be so uniform that it results in the absence of a significant acoustic impedance gradient required for the occurrence of shear waves. Monotonic changes in the elastic properties in the transition zone often interfere with the selection and refracting seismic boundaries. Hodographs of refracted waves indicate a smooth increase in seismic velocities with depth (refraction), which is usually characteristic of a gradient medium. Based on the theory of Rayleigh waves, in a homogeneous medium, resonance phenomena are absent, and spectral relations are directly dependent on elastic parameters of the medium, for example, the magnitude of ellipticity (H/V) is inversely proportional to the Poisson coefficient. With maximum changes in the Poisson ratio from 0.5 to zero, the theoretical values of the H/V ratios in a homogeneous medium lie approximately within 0.55–0.8 (Tuan, 2009). In practice, the range is much wider, due to the resonances of different types of seismic waves, under which both horizontal and vertical components of oscillations can increase many times. As a result, it seems quite problematic to carry out any quantitative correlation links between the spectral ratios

of the orthogonal components of microseisms and the elastic parameters of the medium. It is more efficient to isolate the anomalous effects that occur at the interfaces between the media, especially since they are present on most sections.

The following two examples demonstrate the presence of significant resonances of transverse waves at the boundaries of rocky foundations, covered with loose sediments. Both examples were obtained on the territory of the Berezovsky ore field in the Sverdlovsk region. The Berezovsky field is the largest gold ore object of the classical quartz-vein type in the Urals. The mine workings pass through dykes of granitoid porphyry containing gold-bearing quartz veins. The host rocks of the ore field are volcanics and volcanogenic-sedimentary strata of the oceanic complex (Sazonov et al., 1999). Before the revolution, granitoids weathering crust was intensively developed near the surface and to a depth of two tens of meters. In a similar place, in the area of old mine workings, complex seismic studies were carried out. The quaternary rocks in the section are represented by a layer of eluvial loams and sandy loams, which, in turn, are covered by deluvial sediments and bulk soils. According to the results of seismic prospecting of high-frequency explosives, a refractive boundary is surely distinguished at the velocity section, separating the bedrock from the loose formations covering them (Fig. 3).

Microseismic sensing also clearly indicates the presence of a resonant boundary at the same depths (see Fig. 3 a). The ellipticity of microseisms varies widely ($H/V = 2.5 \div 6$), which indicates the heterogeneity of the values of the acoustic rigidity of the contacting media. Nevertheless, the difference of values is quite high and the anomalous effect is manifested throughout the entire profile, without breaking the resonant boundary. Elevated values of the H/V relationship can be one of the signs of identification of underground workings, since the boundary of the undermined space is very contrast in terms of the acoustic properties of two environments.

The next research site is located on the northern periphery of the Berezovsky ore field, within the Pyshminsko-Berezovsky hyperbasite array composed of serpentinites. Here, the behavior of the ellipticity of microseismic background over a layered medium

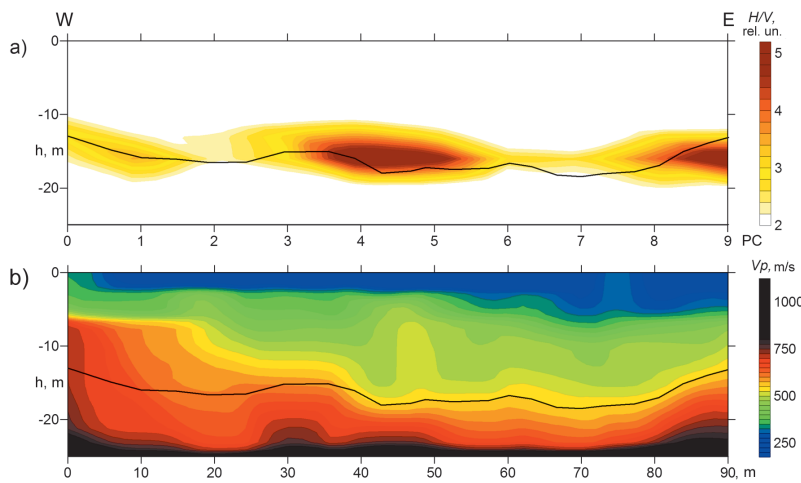


Fig. 3. Comparison of the results of shallow seismic soundings and seismic exploration of small-scale rock formations in the area of the old mine workings of the Berezovsky gold field (Middle Urals): a) H/V relationship section; b) high-speed seismic section of longitudinal waves. The solid line shows the refracting border.

indicates the difference in the physical principles of separation of resonant and refracting boundaries (Fig. 4).

At the beginning of the profile (PC0-10), these boundaries almost coincide, then in the area of the bedrock ledge (PC32) the refracting boundary experiences a drop, and the resonant one almost does not change. Vertical heterogeneity near the ledge is marked by a decrease in ellipticity, almost to the complete disappearance of the anomaly. In the area of PC40-60, both borders become horizontal, but at different levels, with a difference of approximately one and a half meters. These inconsistencies can be explained by the difference in behavior of various types of seismic waves. The refractive boundary was calculated from the hodographs of the longitudinal waves, and the boundary distinguished by the peak values of the microseism ellipticity is due to the resonance of transverse waves. It is known that the behavior of longitudinal and transverse waves in an inhomogeneous medium may differ from each other, which is observed in the above example. Drilling data indicate that the seismic exploration results of the MOR are more reliable, since the refractive boundary more accurately determines the depth of the bedrock than the resonance boundary (Fig. 4).

The following example was obtained at the Pyshminsk-Klyuchevsky ore field. The Pyshminsky copper mine operated from the middle of the 19th century until 1976.

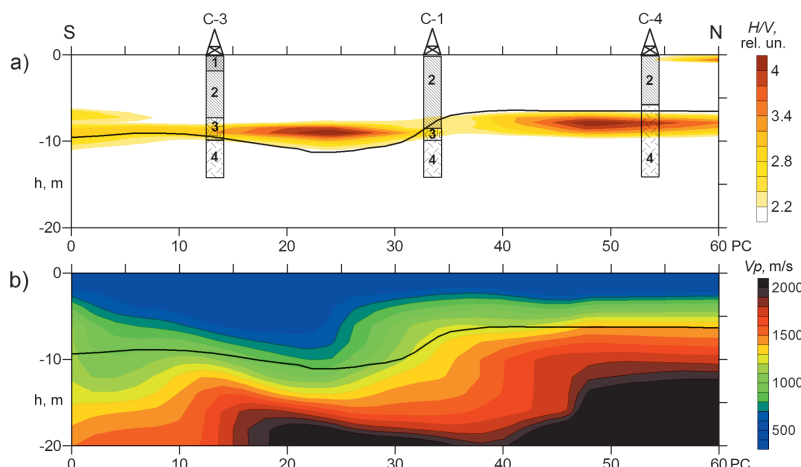


Fig. 4. Comparison of the results of the shallow seismic sounding and the seismic exploration of the MPS at the site of the development of serpentinites: a) H/V relationship section; b) high-speed seismic section of longitudinal waves. The solid line shows the refracting border. Designations of geological columns: 1) bulk soil; 2) loam; 3) gravelly-rubby soil; 4) fractured serpentinites.

Ore zones of the field have a submeridional strike and occur in volcanogenic and volcanogenic-sedimentary rocks of medium and basic composition. In addition to copper, cobalt, gold, and silver were mined at the mine. Prospectors were involved in the development of high-grade ores, so the entire territory of the ore field was subjected to additional work. The research profile was held in the area of the old mine workings of a not deep foundation. A shallow seismic survey revealed two refracting boundaries and sharp drops in the relief of the bedrock surface, represented by porphyritic andesite-basalt (Fig. 5).

The emergence of two resonant boundaries is confidently observed at depths corresponding to the refracting horizons. The high allocation contrast should be noted of the horizontal borders of the excavations found in the range of 60-80 meters, and at the end of the profile (Fig. 5 a). It is noticed that the greatest intensity of the resonance is confined to small hollows and angular sections of the change in the surface of geological boundaries.

The list of objects we study with the help of MRZ facilities includes earth dams, to which a separate article was devoted. The main conclusions of this publication (Davydov, 2016b) are as follows:

- microseismic soundings, based on the study of horizontal and vertical components of oscillations, make

it possible to distinguish the main features of the deep structure of earth dams;

- according to the results of the comparison, the resonance boundaries in half of the cases coincide with the refractive seismic boundaries, but are distinguished by extreme inconsistency;
- in addition to the resonance of transverse waves, there may exist resonances of other seismic waves, characterized by a significant dominance of the amplitude of vertical displacements over horizontal ones;
- artificial structures in the body of dams (spillways, wells, etc.) have their own characteristic resonant frequencies associated with the natural vibrations of individual structural elements.

The main provisions of this conclusion can be demonstrated by examining the low-altitude dam of a rural pond on the river Aramilka (Fig. 6).

The features of the microseismic section include an anomaly in the area of the weir, due to the resonance of the structure. The resonance boundary at the base of the dam approximately coincides with the refractive boundary, but is highly discontinuous. It exists rather in the form of separate sites in which the magnitude of the resonance $H/V \geq 2$. Under such conditions, it is difficult to clearly identify the bulk part of the dam without additional research methods, for example, such as shallow seismic exploration or electromagnetic sounding (Fig. 6 b). The vagueness of the resonance boundaries on the dams is due to the full water saturation of the

contact between the base and the bulk part, due to which the difference in seismic velocities and, accordingly, acoustic impedances is not sufficiently sharp. Practice shows that the nature and magnitude of the resonant peaks of the spectral relations are influenced by: the material composition of bedrock, the granulometric composition of loose sediments, porosity, water saturation, and many other factors.

As already noted, resonance phenomena may be present not only at horizontal interfaces, but also at vertical ones. First of all, this refers to the contacts of rocks that differ in composition, for example, gabbro and granite (Fig. 7).

The contact position of two intrusions (PC20) is confidently determined by radiometry data, since granites usually have a higher gamma activity compared to gabbros. On the section of the H/V relationship, this contact appears as a vertical anomaly of elevated ellipticity values; the horizontal anomaly corresponds to the top of the source rock. The source rock is covered with loose sediments with a thickness of 6-7 meters in the area of gabbro distribution (PC0-20), increasing to 10-12 meters above the granites (PC20-40). The sub-horizontal boundary of the overburden is well distinguished near the contact of two arrays and disappears after 150 meters on either side of it. Such behavior of resonant boundaries can be associated with partial watering of the zone of contact between rocks, which increases the contrast of acoustic stiffness. At long

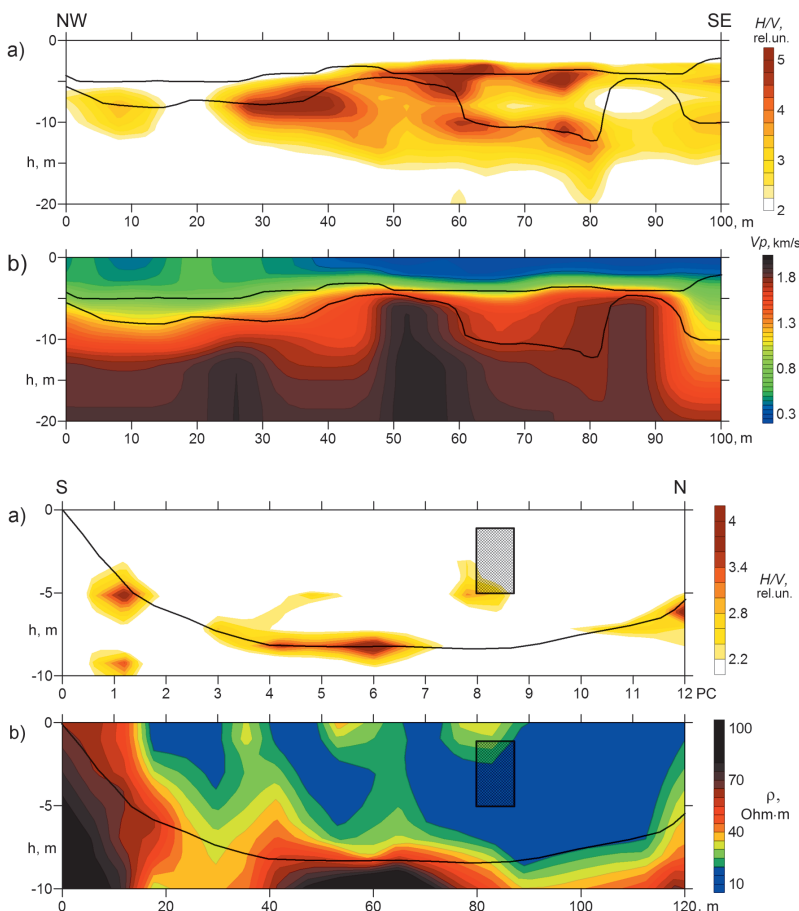


Fig. 5. Comparison of the results of microseismic soundings and seismic exploration of small-scale rock formations in the area of mine workings at the Pyshminsko-Klyuchevsky copper-cobalt field (Middle Urals): a) section of the H/V relationship; b) high-speed seismic section of longitudinal waves. The solid line shows the refracting boundaries.

Fig. 6. Comparison of the results of microseismic and electrical soundings on the dam. Of Aramilka river: a) spectral H/V relations section; b) a two-dimensional geoelectrical section (ρ is the specific electrical resistance). The solid line shows the refracting border, the shaded area corresponds to the weir.

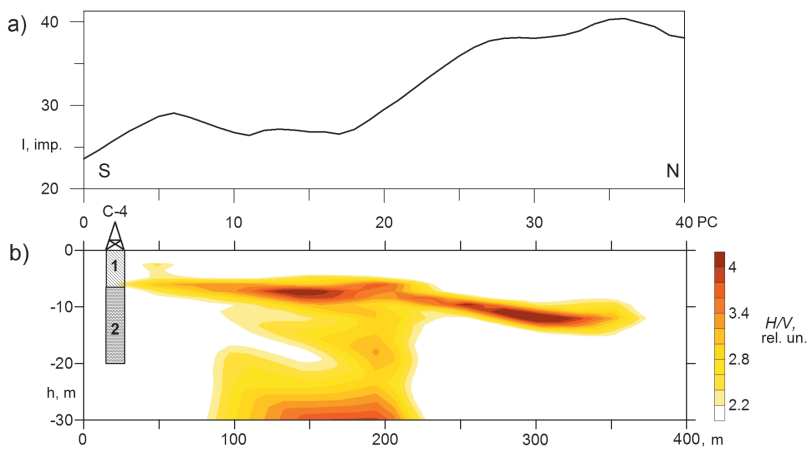


Fig. 7. The results of geophysical work in the contact area of the Novo-Alekseevsky gabbro and Verkh-Isetsy granitic arrays (Middle Ural): a) graph of the intensity of the background radiation; b) H/V-relations section. The designations of the geological column: 1) Diluvial loam; 2) gabbro.

distances from the boundary of the arrays, it appears that a more gradual change in the elastic properties from rocky soils to loose sediments occurs. As a result, the resonance does not occur and the horizontal interface is not manifested by the shallow seismic sounding. Of the other features of the section, it should be noted that the wide anomalous region in the area of the PC10-20 pickets belongs to the near-contact zone of modified rocks with increased fracturing.

Tectonic disturbances in microseismic sections are also highlighted by elevated values of ellipticity. In this case, anomalies may occur in the upper part of the section and be absent at depth. So, in the Yngay region of the Rai-Iz array, two tectonic discontinuities were distinguished from the surface, characterized by a strong disintegration and dissemination of the dunite-harzburgite complex of rocks (Fig. 8).

According to the results of induction soundings, it was found that the propagation of one of the tectonic cracks (PC2-4) to a depth of more than 40 meters. However, the corresponding vertical anomaly of the ellipticity was displayed in the section only to a depth of about 15 meters. The depth of the other dislocation (PC10) according to the results of microseismic and induction soundings approximately coincides. The resonance phenomena on the vertical borders of the sections are still little studied, so it is too early to draw any conclusions about them. The main thing is that they exist and require further study.

Conclusions

The presented results show the complex nature of the ellipticity of microseismic noise under different conditions, however, in some cases, they allow determining the main boundaries of the section of the upper part of the geological section. The resonant boundaries emitted by means of microseisms are often located close to or coincide with refracting seismic boundaries. This is in complete agreement with the theory that both resonance effects and refracted waves appear at the interface between two media with a large contrast of acoustic rigidity. The discrepancy between the boundaries obtained as a result of the resonance of transverse (S) waves and the refracting boundaries found by the longitudinal (P) wavegraphs is probably due to the difference in the behavior of P and S waves in inhomogeneous media. The absence of resonance peaks of the ellipticity of the microseism can indicate either the homogeneity of the medium or the smooth changes in the acoustic properties at the boundaries of the sections that prevent the occurrence of resonance.

In the course of experimental work, it was found that with a change in the azimuth of a horizontal seismometer, the amplitude of the corresponding signal component usually changes, but the shape of the spectrum remains relatively stable. Thus, the sections of the spectral relations retain their main characteristics, regardless of the direction of the observations.

The technology of shallow seismic soundings based

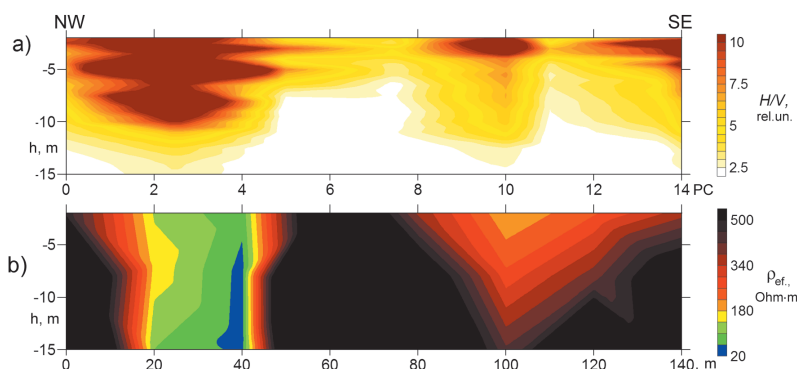


Fig. 8. The results of geophysical studies on the Yngaysky section of the ultramafic Rai-Iz array (Polar Urals): a) a section of the spectral H/V relationships; b) the section of effective (apparent) resistances.

on the study of the ellipticity of microseisms is desirable to be used in combination with other geophysical methods. When interpreting, it is necessary to be guided by the experience of previously performed work on the closest analogues, as well as to conduct parametric studies on control profiles with a known geological structure.

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