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SEISMIC WAVE FIELDS PROPAGATION IN INHOMOGENEOUS MEDIUMS

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SUMMARY

A comparison has been made between seismic effects of identical basic parameters recorded within the sites of various rocky ground conditions – thawed, plastic frozen and stiffly frozen. Notice that spectra of stiffly frozen ground motions are of lower frequency structure than those of thawed and plastic frozen ground motions. Consideration has been given to experimental frequency characteristics of the mediums presented by thawed and plastic frozen grounds obtained in relation to stiffly frozen grounds. The frequency characteristics computed from seismic simulation pursued for depths ranging from 0 to 8 km are considered for all the sites. On the one hand, a combined analysis of experimental and computed frequency characteristics makes it possible to distinguish the upper section layer, in which seismic signals from earthquakes are the most scattered. On the other hand, it allows differentiating the influence of deep-seated and near-surface inhomogeneities into dynamic characteristics of seismic signals.

INTRODUCTION

To pursue a seismic simulation to study dynamic characteristics of synthesized seismic fields, it is important to evaluate the degree and depth to which seismic characteristics of a half-space are to be determined to provide an available accuracy of calculations of relative parameters of probable seismic ground motions. Two types of models have been used for computational methods. First, these models took into account seismic fields, reflected and imposed on the basic signal, and other factors influencing on the accuracy of simulation to analyze new calculation data and compare them with the experimental data obtained from earthquakes. Second, these models reflected the uppermost section, in which the man-made changes of properties of the investigated grounds, especially of those originally frozen, can be expected.

The solution of this problem for the Baikal seismic zone has been started from the above two-type simulation up to depths ranging from 8 to 12 km. One hand, it gave the chance to differentiate between the influence of deep-seated and near-surface inhomogeneities (mainly stratigraphic interfaces close to plane-parallel – regular) on dynamic characteristics of seismic signal. On the other hand, it allowed

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evaluating distributions of irregular ("random") inhomogeneities. Of importance is also the fact that a direct comparison has been made between the spectra of probable motions of rocky grounds that are in various conditions from stiffly frozen to thawed – at earthquakes with nearly identical parameters, *K* and Δ. Experimental and model investigations have been pursued on these grounds, thawed and frozen in different parts of the Baikal rift zone. Velocity sections obtained by deep, intermediate- and shallow-depth seismic sounding provided the basis for the seismic simulation (Fig. 1), Krylov, [1].

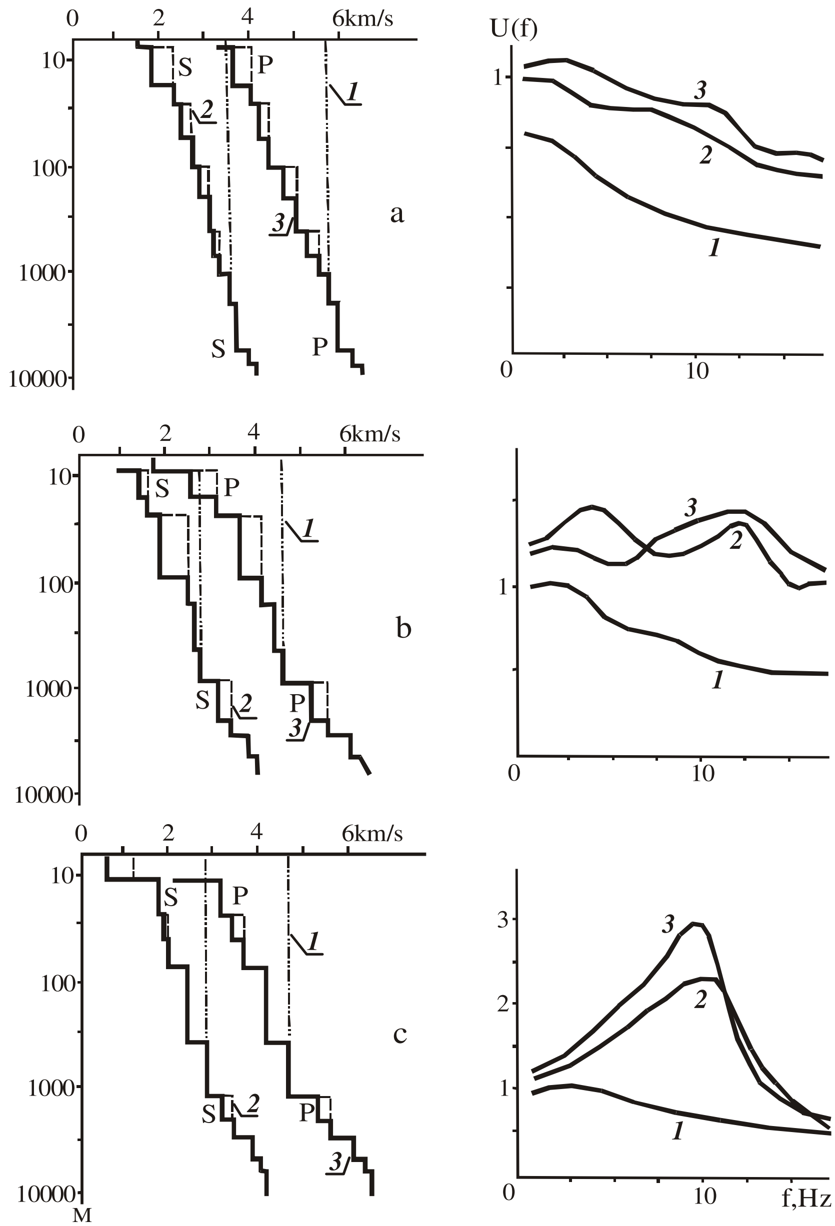

Fig. 1. Seismic models
(1 –only based on the deep seismic sounding data; 2, 3 – based on the deep and shallow seismic sounding data) and appropriate computational parameters (1-3) for stiffly frozen (a), plastic frozen (b) and thawed (c) rocky grounds of the Baikal seismic zone.

A BRIEF CHARACTERISTIC OF GROUNDS AND VELOCITY SECTIONS

The first site (stiffly frozen grounds) is dominated by the distribution of the Late Paleozoic granitoids, presented by medium-grained granites in the earthquake recording point. Their specific fracturing is 8-10, sometimes 20%. An ice is observed in the massif along the fractures. A volumetric ice-content ranges from 3 to 11%. The coefficient of fractured hollowness ranges from 0.16 to 0.37. The limit of strength of compression of the frozen medium-grained granites ranges from 108 to 186 MPa, the permafrost is 300-400 m in thickness, and the temperature is $-3 \div -5^0$C (stiffly frozen condition). In the uppermost section the velocities of seismic waves are high, making 3.2 km/s for longitudinal (Vp) and 1.5 km/s for transverse (Vs) waves. At a depth of 8 km they make 4 and 2.3 km/s respectively.

On the second site (plastic frozen grounds) the Riphean-Paleozoic granitoids and gabbroids of various textures compose the complex of volcanic rocks. The granites present the rocky grounds in recording point in the upper section. Their velocities are Vp = 1.7 km/s and Vs = 0.9 km/s up to depth of 12 m, and 4 and 2.4 km/s respectively at a depth of more than 100 meters. The basic characteristics of physical-mechanical properties of rocky grounds are the following: volumetric weight $2.4 \div 2.65$ g/sm^3, porosity $8 \div 16\%$, volumetric ice-content $2 \div 7\%$, and temporal resistance to compression $40 \div 110$ MPa. The frozen grounds are 23 m in thickness and have temperature $0 \div -0.5^0$C (plastic frozen condition).

The above-presented characteristics correspond to the upper section of rocky grounds up to the depths that do not exceed 30 m from the surface.

The Archean gneisses, schists, amphibolites and quartzites are widely spread in the third site (thawed grounds). In the point of making instrumental measurements the outcrops are presented by badly fractured gneisses (Vp = 1.15 km/s; Vs = 0.52 km/s) up to depth of 14 m. The velocity continuously increases with depth. The volumetric weight of gneisses is 2.4-2.6 g/sm^3, porosity is 6-18 %, and a temporal resistance to compression is 20-90 MPa (thawed water-unsaturated condition).

As a first approximation, the velocity section for the first and second sites is presented by four and six layers with Vp ranging from 5.7 to 6.4 km/s and from 4.5 to 6.4 km/s respectively (Fig. 1).

The third site is located near the area of transition from the Siberian platform to the Baikal folded area. The Siberian platform is characterized by nearly horizontal boundaries in the earth's crust. The first refracting boundary of the crystalline basement reaches depth of 2-3 km and has boundary velocity of 5.1 km/s. The boundary velocity of the basement surface is sustained ranging from 6.1 to 6.2 km/s. The refracting horizon with Vp = 6.3-6.4 km/s develops below the basement surface at a depth of 5-8 km.

The refracting boundaries are vague with transition to the Baikal rift zone. The velocity section is characterized by velocity isolines obtained from the data on refracted waves. The plots averaged for the parts of temporal field waves no less than 120-170 km in length related the velocity to depth. As a result of such interpretation, Krylov [1], the five-layer section with velocities ranging from 4.5 to 6.4 km/s is typical of the third site.

The models obtained from the deep seismic sounding data were specified by velocity measurements made by refracted wave method up to depths of 200 m and presented by two additional models for each of the sites. It is due to the fact that the basic refracting boundaries are kept, and continuous change of velocities with depth revealed from hodographs of the refracted waves was presented by different quantity of the plane-parallel layers. The evaluation of influence of physical properties of the rocks of the upper section on dynamic characteristics of seismic waves has thereby become possible, Vakhromeev [2].

The following regularities are noteworthy as a whole. The layers grow in number from frozen to plastic frozen and thawed aerial-dry rocky grounds. A proportion of pores and fractures filled with water and ice decreases to zero, and the fracturing of original rocks almost does not change. The velocities of seismic waves (Vp and Vs) and the limits of strength of compression decrease in the process.

Earthquake spectra, experimental and computed frequency characteristics of the upper section

Theoretical calculations have been made from the COEF-10 program of Ratnikova [3] that is used to calculate oscillations of a free surface of slightly absorbing packet lying on elastic half-space. In this case frequency characteristics U(f) have been only calculated.

The earth's crust layer at a depth of 8 m has been selected as elastic half-space. It is due to the fact that velocities of seismic waves are comparable at this depth for the three investigated sites giving the chance to compare the results of calculations for each of the models. The small earthquake (Δ = 30 km, K = 8) recorded on stiffly frozen ground has been selected as an initial signal for calculations.

Frequency characteristics U(f) computed for the models show that specification of velocities of seismic waves in the upper section results in the increase of level of frequency characteristics for all the models (in relation to the curve computed for the model obtained from deep seismic sounding). The level of the curves can increase 4-5 times with transition from stiffly frozen to thawed rocky grounds (Fig. 1).

We emphasize the following to describe the earthquake recording. Engineering-seismological testing grounds were located in different time periods on the sites selected for comparison. The rocky grounds, the models of which are shown in Fig. 1, have served as a standard. That is why these sites yielded the greatest quantity of the statistical data on earthquakes. More than 500 earthquakes of 7-10 energy classes (K) with epicentral distances (Δ) 27-350 km have been recorded as a whole. It allowed selecting the earthquakes with K and Δ equal for the three sites to make a comparative analysis of dynamics of rocky ground motions.

The spectra of seismic signals have been obtained in a wide range of epicentral distances ($\Delta = 27 \div 350$ km) for the above-mentioned sites. The resolution of spectra was assigned in accordance with frequency and in most cases made 1.5 Hz that provided a relative (maximum) error of the spectrum in frequency band 0.5-16 Hz equal to 20%. As a result it has been determined that the level of spectra of thawed ground motions at high frequencies is abnormally high as compared with that of frozen ground motions, Pavlov, [4]. So, the spectra of earthquakes of the same energy class and epicentral distance show that the level of seismic signal on thawed grounds is much higher than that on frozen grounds on the frequencies exceeding 5 Hz (Fig. 2a, b). The spectrum of plastic frozen ground motions takes an intermediate position (Fig. 2a, curve 2). As it takes place, the average spectra obtained from 10 and 3 earthquake records have been selected for the first and second sites respectively (curves 1, 2).

The dominance of high-frequency components in the spectra of earthquakes recorded on thawed grounds is visualized from their ratio of $K(f)$ to the spectra obtained for frozen rocky grounds (Fig. 2d). The greatest values reaching 8-9 correspond to the ratio of thawed ground motion spectra to stiffly frozen rocky ground motion spectra. In this case, the levels of maximums $K(f)$ do not almost depend on the epicentral distance (curves 1 and 2). The ratio of thawed ground motion spectra to plastic frozen ground motion spectra reaches 5 at frequencies of 7 and 12 Hz (curve 3). The ratio of plastic frozen ground motion spectra to stiffly frozen ground motion spectra has the least values not exceeding 2-3 (curve 4).

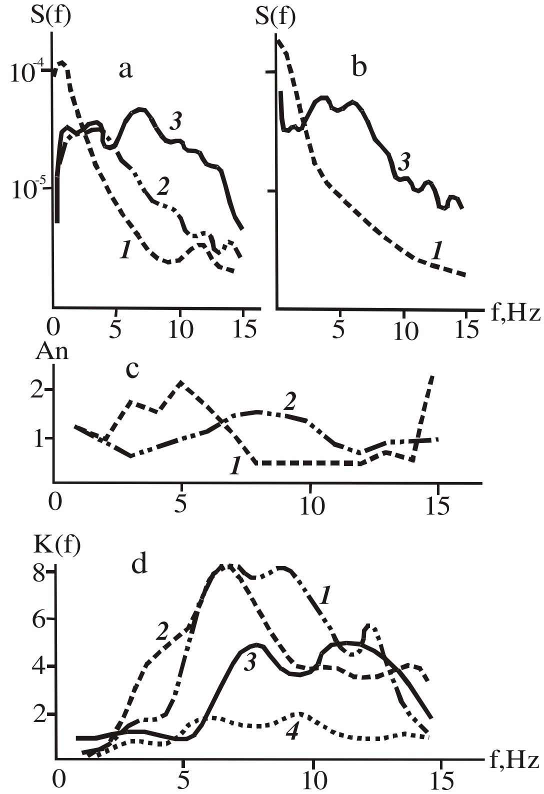

Fig. 2. Experimental data on the spectra and relative frequency characteristics form the earthquakes recorded on rocky grounds of a different condition.

a – spectra of Δ = 30 km earthquakes, K = 9 (1 – stiffly frozen; 2 – plastic frozen; 3 – thawed); b – spectra of Δ = 300 km earthquakes, K = 10 (stiffly frozen, 3 – thawed); c – ratio of the spectra of near earthquakes (Δ = 30 km) to those of distant earthquakes (Δ = 300 km) (1 for frozen rocky grounds; 2 – for thawed grounds); d – ratio of the spectra of motions of rocky grounds of a different condition (1 – thawed to stiffly frozen (Δ = 30 km), 2 – thawed to stiffly frozen (Δ = 300 km), 3 – thawed to plastic frozen, 4 – plastic frozen to stiffly frozen).

If the ratio of 05:1.5 is considered to be significant, Pavlov [4], we obtain that the spectra of stiffly frozen ground motions are overestimated at frequencies higher than 2.7 Hz and underestimated at frequencies lower than 1.8-2.3 Hz to the spectra of thawed and plastic frozen rocky ground motions. A similar behavior of seismic signals in propagating in less consolidated rocky grounds, to which thawed fractured grounds are related can not be due to their absorbing properties.

The ratios of spectral components of the motions at near earthquakes to those at distant earthquakes with the increase of frequency are shown in Fig. 2c (for thawed (2) and frozen (1) grounds). A general reduction of the ratio of spectral densities with the increase of frequency is typical of seismic signals recorded on thawed grounds (curve 2), whereas the ratios of spectral components of distant and near earthquakes recorded on frozen rocky grounds do not generally depend on frequency (curve 1). A comparison between the curves of Fig. 2c shows that K(f) for the distant earthquakes can be about 2 times overestimated at frequencies 2-6.5 Hz (Fig. 2d; curves 1, 2) and about 2-3 times underestimated at frequencies 6.5-10 Hz and higher. Comparing dependency K(f) (curves 1-4), it is believed that seismic signal is redistributed from low frequency area to high frequency area in less consolidated mediums at the cost of considerable scattering of the low frequency component of the wave field on small inhomogeneities with further imposing of scattered waves on the primary signal.

The experimental and computed spectral characteristics have been obtained from the use of identical approach (from the ratio of thawed ground motion spectra to frozen ground motion spectra). Considered in combination (Fig. 1 and 2), they show a good correlation between each other in the basic maximum level at frequencies exceeding 3 Hz. On low frequencies the differences are considerable. From the behavior of the calculated curves one can conclude that the obtained results do not contradict the general ideas based on the fact that the spectral level on monolithic frozen rocky grounds in the investigated frequency bands is in the average lower than on thawed fractured grounds.

The results of computational methods have clearly differentiated the influence of structural inhomogeneities and inhomogeneities of the uppermost section on the intensity of seismic motions. The structural inhomogeneities make themselves evident at frequency characteristics calculated for the models obtained from the deep seismic sounding data (Fig. 1, models a-c, curve 1), and the inhomogeneities of the uppermost section show up along curves 2 and 3 calculated from models 2 and 3. The change of seismic motion intensity due to the upper section can be evaluated from the ratio of curves 2 and 3 to curve 1 with regard to frequency. Such analysis suggests decreasing influence of inhomogeneities of the upper section and increasing influence of structural inhomogeneities on the intensity of seismic motions of initial signal with decreasing frequency. From 5 to 15 Hz, the certain models (Fig. 1) are dominated by the influence of inhomogeneities of the upper section 200-300 m in depth. From 3 to 5 Hz, the contribution to intensification of motions of the initial signal becomes equal, and on further decreasing of frequency the influence of the near-surface inhomogeneities becomes minimum as compared with that of the deep-seated inhomogeneities.

Considering rocky grounds cemented by ice as the most homogeneous, the difference in the influence of structural and near-surface inhomogeneities on the initial signal can be evaluated directly from the spectra of displacements of frozen and thawed grounds and from their ratio in accordance with the experimental data. Taking into consideration the data of Fig. 2d and the above analysis, notice that the character of the variation of seismic motion intensity by the structural and near-surface inhomogeneities from 15 to 3 Hz corresponds to the calculation data. The character of the variation of intensity of the initial motions obtained by the computational methods retains with further decreasing of frequency.

The variation of frequency characteristics K(f) with increasing frequency in Fig. 2d suggests the following:

1) At relatively low frequencies – from 0.5 to 2.5 Hz – (the ratio of the maximum to the minimum frequency is 5) the intensity of seismic signal recorded on stiffly frozen grounds (as compared to that recorded on thawed grounds) decreases from 0.16 to 1 according to the above frequency range.

2) At frequencies from 2.5 to 15 Hz (the ratio of f_{max} to f_{min} is 6) there is an intensive imposing of high-frequency scattered waves. The intensity of seismic signal varies from 1 at frequency 2.5 Hz to 4-10 at frequency 7-10 Hz with regard the ground conditions in which the seismic signal is recorded (in this case the values for plastic frozen and thawed rocky grounds are presented).

3) It seems likely that scattering of the seismic field is mainly due to the upper rocky ground layer about 1000 m thick. Considering that the actual seismic signal propagates at some angle to the horizontal surface, it can correlate approximately with wavelength λ corresponding to 1 Hz. Nevertheless, the thickness of layer that scatters the seismic signal in the most intensive way will be within the 1000-m thick layer. It can obviously result from the following:

a) Less bound and more differentiated inhomogeneities of the upper section.

b) Intensive wave scattering on different marginal inhomogeneities (close to the site) followed by summation of incoherent scattered waves in the site.

The intensity of diffracted, converted and other waves that are assigned to scattered waves should generally exceed the intensity of scattered waves accumulated by the medium in the course of propagation of seismic signal from the source to the site. This excess is due to the fact that inhomogeneities in depth and near the surface differ in scale, and to rather intensive absorption of high frequency components of the previously scattered waves by the medium.

4) There is no question that the spectral form on the surface can be determined by three-four non-alternative factors:
a) Repeatedly scattered seismic waves, as the increase of repetition results in a sharp increase of intensity of scattered waves in the observed signal.
b) Probable intensive scattering of seismic waves in the near-surface layer about 1000 m in thickness that neither exceeds the wavelength nor excludes the repeated scattering within this layer with the following summation of these waves in this site. The latter is supported by the fact that a relative frequency characteristic of the medium is almost identical on thawed grounds for both earthquake with ~30 km epicentral distance and earthquake with ~300 km epicentral distance, i.e. for the earthquakes with epicentral distances ten times different. The same is indicated by the curve obtained for the characteristics of an integral absorption of the medium (Fig. 2c)).
c) An intensive formation of surface waves in the upper layer followed by conversion scattering of S-R and R-S types, as a clear extension of frequency band of the spectrum is observed for thawed ground motions. So, if spectral density drops by an order in the range from 4 to 5 Hz on stiffly frozen grounds with regard to epicentral distance, it decreases by the same value on thawed rocky grounds at 15 Hz and higher frequency.
d) High-frequency components of the scattered waves arriving from different directions (lateral scattering) impose on the basic seismic signal.

Formation of seismic signal and, therefore, the spectrum of it will most likely be influenced by all above-mentioned factors. The question is which of these factors is dominating.

It is believed that the velocity of seismic wave propagation in the upper layer of stiffly frozen rocky grounds approximates adequately to that for thawed rocky grounds at some depth in elastic area. If so, the less is the velocity gradient with depth, the lower is the frequency of seismic signals recorded on the surface at a site. Consequently, it suggests that the frequency structure of seismic signal is inversely proportional to the gradient of velocity of seismic wave propagation with depth. It is in agreement with the results obtained by O.K. Kondratyev [5] in studies of synthetic seismograms but in temporal area. As well as we do, he attributes this phenomenon to scattering of seismic waves on inhomogeneities of the medium.

However, considerations of this effect (reduction of frequency with depth) in frequency area lead to somewhat different conclusion. Namely, it suggests that the proportion of high-frequency components increases at the cost of scattering of low-frequency part of the wave field on small inhomogeneities of the medium throughout the source-site trace. Then come imposing on the basic signal and, therefore, corresponding redistribution of the intensity of high and low frequency components in the seismic signal recorded on the surface.

Thus, it is felt that the variation of frequency structure with depth is due to scattering of low-frequency component by small-scaled inhomogeneities of the medium. It is supported as well by the results obtained in Drennov [6]. Leaning upon the experimental data obtained by a small aperture group, it is shown that the first approximation radius of correlation of the wave field is inversely proportional to the frequency squared.

Recognition of irregular inhomogeneities of the upper section of the earth's crust

In this section an attempt has been made to recognize irregular inhomogeneities from the data of the previous section.

L.I. Ratnikova's program [3] is based on the radial theory of propagation of seismic waves. That is why frequency characteristics calculated by this program reflect mostly the influence of large-scaled inhomogeneities ($a>\lambda$) or at least the inhomogenities that have rather contrast interfaces and the only solution for the section model (absence of random inhomogeneities). As this takes place, the program is applicable to plain-parallel bedding of the layered inhomogeneities.

Propagating through the medium, the actual seismic signal is "automatically" influenced by inhomogeneities of all types. As a result the frequency characteristic of the medium is determined by both radial and wave effects (like Frenel or Fraungofer difraction on various inhomogeneities including gentle-contrast interfaces between them).

Having divided the frequency characteristic of the medium (K(f)) obtained from actual seismic signal into the frequency characteristic of the medium calculated from the COEF-10 program (U(f)) we obtain also the frequency characteristic of the medium in which seismic signal is propagating. This medium determines only the wave effects of the interaction between seismic signal and medium (Fig. 3) – effects of scattering on "random" inhomogeneities of the medium. As this takes place, a probable influence of plane-parallel contrast interfaces on seismic signal is excluded as the latter are taken into consideration in calculating frequency characteristics.

A comparison between the ratios of frequency characteristics has been made for two cases. In the first case (Fig. 3a, b, c) the ratio included frequency characteristic that has been calculated from the model obtained basically from the data on shallow-depth and deep seismic sounding for the surface of corresponding rocky ground. In the second case it included frequency characteristic obtained at a depth of 1000 m and only corresponding to the deep seismic sounding data (Fig. 3d, e). Of course, the exclusion of geometrical approximation is of qualitative rather than of quantitative character, as the velocity models themselves are obtained from the averaged profile observations, especially the velocity sections of deep seismic sounding. In doing so, the frequency characteristics of the medium obtained from individual earthquake spectra for thawed grounds have been assigned to the average spectrum obtained from 7-10 recordings (with regard to Δ, K etc.) on stiffly frozen rocky ground. At any case the parameters of these earthquakes were close, both in selecting the spectra of stiffly frozen rocky ground motions for averaging and in comparing the spectra of thawed, plastic frozen and stiffly frozen rocky ground motions.

As a result we have obtained the ratios of frequency characteristics of the medium determined on the surface. More composite in their form, these ratios were found to be almost twice lower in their level for all types of rocky grounds than the ratios of frequency characteristics of the medium computed only from the deep seismic sounding data (Fig. 3d, e). The character of K(f)/U(f) distribution of frequency changes at the same time, manifested as comparability of their maximums at frequencies of about 6-7 Hz and 13-15 Hz that obviously reflects scattering properties of irregular (random) inhomogeneities of the uppermost section. At frequencies ≤ 2.5 Hz the level of ratios of frequency characteristics is much lower than 1 or comparable with it. At frequencies ≥ 2.5 Hz this ratio is 10 for thawed rocky grounds and 4 for plastic frozen grounds. Thus at frequencies ≥ 2.5 Hz the seismic signal consists only of scattered component and absorbing properties of the medium become practically indeterminate.

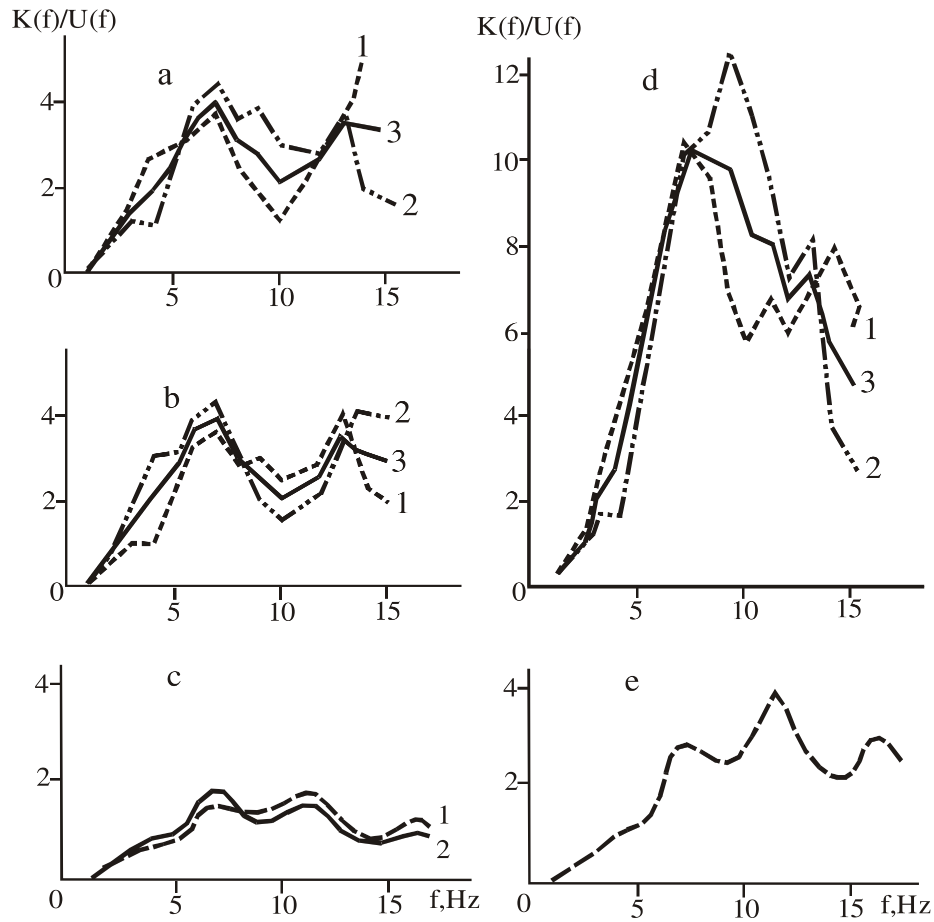

Fig. 3. Ratios of experimental K(f) to computational U(f) frequency characteristics for rocky grounds.

a –thawed grounds, U(f) (Fig. 1c, 2, 3) computed on the surface, K(f) (Fig. 2d, 1) computed from near earthquakes (Δ = 30 km); b – thawed grounds, K(f) (Fig. 2d, 2) computed from distant earthquakes (Δ = 300 km); c – plastic frozen rocky grounds, U(f) (Fig. 1b, 2, 3) computed on the surface from the two models respectively; d – thawed grounds, K(f) (Fig. 2d, 1, 2) computed from the Δ = 30 km (1) and Δ = 300 km (2) earthquakes, U(f) (Fig. 1c, 1) computed from seismic models that are only based on the deep seismic sounding data; e – plastic frozen grounds, U(f) (Fig. 1b, 1) computed from the models that are based on the deep seismic sounding data.

1, 2 – curves corresponding to various computed (a, b, c) or experimental (d) frequency characteristics, 3 – a curve averaged for curves 1 and 2.

An actual recurrence of the curves of K(f)/U(f) ratios for the considered mediums concerning different earthquakes indicates also a stable distribution of these inhomogeneities along the source-site trace. Some deviations can be due to both variety of earthquake parameters and certain fluctuations of the mediums in which seismic signals are propagating.

So, the basic changes of seismic motions have been revealed in comparative analyzing the experimental and calculation data from the models obtained from the deep seismic sounding. These changes determine rather reliably the degree of influence of the deep-seated and near-surface inhomogeneities on dynamic characteristics of initial signal in frequency range 1-15 Hz. Spectral characteristics of seismic signals from earthquakes with practically identical parameters can differ widely according to rocky ground they are recorded on. Besides, the differences found in the degree of influence of the deep-seated and near-surface inhomogeneities on seismic signal necessitate using the deep seismic sounding data for certain areas to evaluate their initial seismicity (general seismic zoning). They also generate a need for detail seismic zoning and microzoning from the deep seismic sounding data in combination with the data obtained by shallow-depth geophysics from the study of the upper section.

These results are no less important for substantiation of principles of formation of seismic models with regard to an error for the areas different in seismic, geological and perennially frozen ground conditions. The formation of “standard” model is aimed at solving two problems. First, it is the most substantiated assignment of initial seismicity units to certain ground conditions. Second, it is the calculation of “standard” seismic characteristics of ground motions at earthquakes, the intensity of which correspond to initial seismicity. For a rather reliable level of investigation of the area, the variation of parameters of ground motions throughout the area can be evaluated by computational and experimental methods. It results in a quantitative assessment of seismic hazard that is a set of parameters required for designing of earthquake engineering.

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