METHODS OF ESTIMATING THE EFFECT OF SUPERFICIAL DEPOSITS ON THE INTENSITY OF SEISMIC OSCILLATIONS

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ABSTRACT

The authors consider the main trends in evolving the methods of estimating the effect of the superficial deposits on the intensity of seismic oscillations for the purposes of seismic microzoning being developed at the Institute of Physics of the Earth of the USSR Academy of Sciences. The effect of soils on the intensity of tremors is appraised on the basis of: 1) the sutdy of the velocities of propagation of longitudinal waves in the surface layers of the soil with artificial generation of the tremors; 2) the study of the spectral characteristics of the ground layer from the recordings of natural earthquakes; 3) the study of the microtremors under various ground conditions.

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A conclusion is made that it is reasonable to advance the complex study of the soils by all above methods to obtain the most comprehensive oscillatory characteristics of the soils.

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The estimation of the effect produced by the ground conditions on the intensity of earthquake manifestations is an extremely important task of the engineering seismology. The investigations undertaken by many workers show that the soils with different physical properties may essentially change the intensity of seismic action. The investigation of the results of destructive earthquakes have shown (1) that an increment in the seismic intensity may reach in individual cases 2-3 by the scale accepted in the Soviet Union (1.2). The increase in the seismic intensity depending on the ground conditions is controlled mainly by the thickness of the ground layer and its physico-mechanical elastic properties.

The ground layer oscillations are of resonance nature. The ground amplitudes increase sharply when the period of the seismic waves coincides with the natural period of the surface layer oscillations. These phenomena become quite pronounced where the thickness of the layer is comparable with the length of the seismic waves, i.e., where it is of tens and hundreds of metres. The elastic properties of the rocks underlying a structure control to large extent the behaviour of the structure during seismic oscillations. For this reason, to estimate correctly the effect of soils on the seismic stability of structures, it is necessary to have complete knowledge of the elastic properties of the rocks which make up their foundation. The method based on the measurement of the velocities of longitudinal and transverse waves appears most promising for determining elastic properties of the ground.

The aim of investigating soils as a foundation for constructions should consist in foretelling the behaviour of the ground at seismic oscillations of various spectral composition.

The workers at the Institute of Physics of the Earth of the USSR Academy of Sciences are now developing a method of seismic microzoning based on a number of instrument investigations of ground tremors. The aim for seismic microzoning is to differentiate the zones depending on the intensity of anticipated earthquake manifestations. Microzoning is performed using the map of the seismic zoning of the USSR on a relatively small territory of a town or construction site located within single seismic zone. The seismic intensity of the zone indicated on the map is related to average conditions of the ground represented by clay and loam in a solid state, sands and sandy loams, depth of occurrence of ground waters being over eight metres, and by coarse fragmental rocks, depth of occurrence of ground waters being over six metres. As a result of microzoning the calculated seismic intensity can be decreased or increased by ± 1 due to the effect of the ground conditions (3).

The relation between the seismic wave velocities and the elastic properties of the medium opens up the possibility of obtaining in principle an analytical dependence of the change in the intensity of an earthquake on the physical properties of the ground from the known velocities of propagation of elastic waves. The form of such dependence was suggested by S.V.Medvedev (1) on the basis of the analysis of the results of destructive earthquakes:

$$\Delta n_1 = 1{,}67 \left[lg\,(V_o \rho_o) - lg\,(\vartheta_n \rho_n) \right] \qquad (1)$$

where $v\rho$ is the acoustic hardness of the medium, which is the product of the density ρ and the velocity of the longitudinal waves v. This formula gives an increment of the seismic intensity on the ground characterized by the parameters $v_n \rho_n$ with respect to granite $v_o \rho_o$ taken as a standard. In selecting the parameters which characterize the effective layer of the ground average values of the velocities of longitudinal waves and the densities of this layer (4) are used.

The velocities of propagation of seismic waves is measured during artificial generation of oscillations by impacts. For unsaturated grounds the increment in the seismic intensity is calculated by formula (1), in case of inundated areas, this is also calculated by formula (1), which use the value $v_n \rho_n$ for similar soils in a state of natural humidity. In this case the velocities are found either from the data of measurements taken at other points, where similar layers are located above the ground water level or from the tables of velocitites which are compiled for the region under study and provide data on the change in the velocity during the water saturation process. The increment in the seismic intensity due to a high ground water level h can be calculated from the formula

$$\Delta n_2 = e^{-0{,}04 h^2} \tag{2}$$

This method for determining the change in the seismic intensity through the measurements of the volocities of propagation of the seismic waves generated artificially by a low power source allows a detailed study to be made over vast territories within relatively short time and at small expenditures.

Seismic stations located on various soils record the earthquakes to study the spectral peculiarities of oscillations of the ground layer and its effect on the amplitude and frequency of the seismic oscillations. The effect of the superficial deposits on the intensity of tremors was discussed in a number of papers (5-8). Nearby earthquakes whose epicentres are located less than 350-400 km from the observation points have frequencies from 0.5 to 20-30 cycles. This signifies that when the transverse waves propagate in the upper stratum at a velocity of from 1,300-1,200 m/sec to 150-200 m/sec the seismic oscillations contain waves with the length λ from several metres to several kilometres. If we bear in mind the interference of the waves in the layers whose thickness satisfies the condition $\frac{\lambda}{20} \leq H \leq \lambda$, then the layers from several metres to 1-2 km thick affect the seismic signal from a nearby earthquake. Because of the repeated oscillations in the layer and the interference, the oscillation amplitude on the surface of a loose layer may exceed that on the surface of rocky ground 4 to 6 times.

Analysis of the seismographic records of nearby earthquakes shows that the oscillations caused by a group of transverse waves, in particular by the wave SH (Fig.1), are as a rule most intensive. From this aspect we shall further consider transverse waves.

The condition of the interference of a wave in an elastic layer, H thick, which overlies a harder semispace is

$$H \cdot \cos\theta = K \frac{\lambda}{4} \tag{3}$$

where λ is the length of the wave in the layer, θ - the angle of refraction of the wave on the layer-semispace boundary and K = 1, 2, 3,... .

When K is even the oscillations weaken , when K is odd the oscillations increase to the maximum.

The amplitude on the surface of a loose layer and the position of the maxima and minima by the frequency depend on the thickness of the layer, its physico-mechanical properties (acoustic hardness), the angle of the wave arrival to the layer surface and its duration, as well as on the amplitude frequency spectrum of the incident wave. Fig.2 shows the calculated resonance curves which illustrate the effect of the above factors on the oscillations on the layer surface. The curves are plotted to determine the effect of each of these factors, all the other conditions being equal. It can be seen from the diagrams in Fig.2 that in addition to the increase in the amplitudes and the change in the spectrum the change in the duration of the oscillations depending on the above factors takes place. With layers whose thickness is less than the wavelength and with the angles of wave arrival of $\theta_0 \leq 60^\circ$, due to repeated reflections inside the layer and the interference of the repeatedly reflected waves, the duration of oscillations on the surface of the layer increases as compared with that of the oscillations observed on rocky ground. The duration of the oscillations also increases when the direction of the incident wave approaches the normal direction.

To determine the effect produced by the grounds on the intensity of seismic tremors the earthquakes were recorded at the points with various soils.

Point 1. The soils are composed of gabbro-diabases.
Rocky ground outcrops.

Point 2. The soils are represented by weathered rock.

Point 3. The soils are represented by a sandy loam layer
with gruss, rock debris and volcanic ash,
20-30 metres thick, lying on a bedrock.

Point 4. The soils are represented by a layer of boulders
with rock debris and loose pyroclastics, less than
100 metres thick, lying on a bedrock.

Points 5 and 6. The soils are composed of a layer of loose
Quaternary deposits, its thickness being unknown.

The distance between the points did not exceed 2 km.

At these points we have recorded several dozens of earthquakes with the intensity of 2 to 6.

The ratios of the displacements, velocities and accelerations recorded at points 2-6 to the respective kinematic magnitudes obtained at point 1 are shown in Table 1. It follows from the table that the oscillation amplitudes increase 2-5.5 times on loose soil; in some cases we have observed an anomalous increase in the oscillation amplitudes (over 10 times) . Fig.3a and b illustrates the recordings of the earthquakes with M = 4.5 at a distance of 96 km (Fig.3a) and an earthquake with M = 3.0 at a distance of 45 km (Fig.3b) at points 1-4 and the amplitude frequency spectra which correspond to them. Comparing the spectra of the earthquakes obtained simultaneously for various ground conditions we can distinguish rather clearly in a number of cases the resonance properties of the loose formation. The stronger the upper layer differs by its elastic properties from the underlying rocky floor, the more pronounced these properties are. Fig.4 shows diagrams of the oscillation spectra from the earthquakes at points 2, 3 and 4 against the spectra of point 1.

The following conclusions can be made from the consideration of the calculated resonance curves and the curves of the actual earthquakes:

1. The greater is the difference in the elastic properties of the loose layer and the rocky floor, the greater is the amplitude on the layer surface, and more distinct is the resonance curve.

2. The resonance curve has several maxima, of which the one with the lowest frequency has, as a rule, the maximum amplitude and is rather stable in frequency from earthquake to earthquake.

This makes it possible to forecast a possible seismic action if we know the geology of the area and the seismic properties of the rocks of which it is composed.

3. As the thickness of the layer decreases the resonance curves shift to the high-frequency region. In the case of nearby earthquakes high velocities and accelerations of the ground tremor can be expected at the points with loose sediments several tens of metres thick.

4. The actual resonance curves have a more complex shape as compared to the calculated curves which can be attributed to the difference between the actual geological section and the one accepted in the calculation diagram (horizontal layer on the semispace) and to the difference

between the actual seismic impulse and the sinusoid section.

It follows from the above that in conditions when the bedrocks are covered by a loose layer from 20-30 to 100 metres thick and the acoustic hardness of the latter is 2-5 times smaller than that of the underlying rocky bedding, the oscillation amplitude may increase several times on the surface of the loose rock as compared with the rock within the frequency range from 1 to 6 cycles, which is very near to the oscillation frequencies of most buildings.

Some data necessary to characterize the soils in seismic microzoning can be obtained from the instrument study of microtremors (9,10). The microtremor recordings obtained with the aid of a wide-band apparatus, which registers the displacements at the frequencies from 1.2 to 20 cycles at an amplification of about 15,000, were used to plot the curves of the recurrency of the periods and the amplitude frequency curves. The latter wer plotted by the averaged amplitudes for the range of periods 0.15-0.5 sec. The investigations (11) of the microtremors and the correlation of the data on the seismic characteristics of the soils, obtained from the study of the microtremors, with the data of the microzoning methods described above lead us to the conclusion that the amplitude frequency curve characterizes the soils most correctly. In this case, care should be taken, of course, that neither regular noise nor noise from a nearby source distorts the results of the recordings.

Fig.5 shows the examples of the recurrency curves and the amplitude frequency curves of micrctremors for the poins with good (point 1), average (point 2) and poor (points 3 and 4) soils. The figure illustrates the data of the measurements of the microtremors at the same points where the earthquakes were registered. The relation of the displacement amplitudes of the microtremors recorded at points 2–6 to the amplitudes observed at point 1 is illustrated in Table 1. The table shows that there is a good agreement with the results of measuring the oscillations caused by the earthquakes.

These methods of determining the seismic properties of soils were used in microzoning of the town of Petropavlovsk on the Kamchatka (11). The scheme of the seismic microzoning of Petropavlovsk was compiled on the basis of engineering and geological data, analyses of seismic oscillations brought about by sufficiency strong earthquakes and the data from the measurements of the microtremors and the data from the measurements of the velocities of propagation of waves. In conformity with this scheme, seismic zones with intensities 7, 8 and 9 were distinguished on the territory of Petropavlovsk.

The study of actual earthquakes under various ground conditions provides a direct answer as to the possible seismic action. To obtain adequate results, however, this method requires an extensive network of seismic stations located on different soils and much time. Two other methods of microzonig (differentiation of the soils by velocities and measurements of microtremors under various ground conditions) prove much more effective in carrying out microzoning in short time and over large areas. The joint application of all the three methods makes it possible to reveal the advantages and shortcomings of each method and the spheres of their application.

Table 1

Nos of observation points	Earthquakes						Microtremors
	Displacement ratio		Velocity ratio		Acceleration ratio		Displacement ratio
	from to	average	from to	average	from to	average	average
2	0.90–1.74	1.32	0.71–2.1	1.48	0.41–4.55	1.99	2.4
3	1.41–6.8	3.52	2.32–10.4	5.03	1.44–16.3	5.69	6.4
4	1.44–6.1	3.71	1.88–8.2	4.00	1.41–7.65	4.49	3.4
5	0.67–2.4	1.47	0.91–3.6	2.17	1.25–4.73	3.06	3.0
6	1.4 –3.4	2.63	0.68–4.47	2.54	1.12–4.61	2.35	3.0

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Captions

Fig.1. Distribution in time (0 -- start of earthquake) of $\frac{A^2}{T^2}$ proportional to the energy of earthquake tremors at points with differing ground conditions:

a) rock;

b) loose soil.

Fig.2. Resonance curves obtained by calculation for the layers:

a) of different thickness: 300, 100 and 30 metres;

b) of different acoustic hardness:

$\frac{\rho V}{\rho_0 V_0} = 0.42$ and $\frac{\rho V}{\rho_0 V_0} = 0.21$ (ρV and $\rho_0 v_0$ - acoustic hardness of the layer and semispace);

c) at different angles of wave arrival to the layer bottom: 63°, 31° and 3°;

d) at various duration of the impulse incident onto the layer in the form of a sinusoid section: 1, 2 and 3 full oscillations.

Fig.3. Example of recording and the amplitude frequency spectrum of an earthquake as registered under various ground conditions:

a - M = 4.5 at a distance of 96 km;

b - M = 3.0 at a distance of 45 km.

The figures correspond to the numbering of the observation points.

Fig.4. Examples of actual resonance curves for nearby earthquakes on Kamchatka as registered simultaneously at points:

a - No.3 , b - No.4 (dash line is the curve of point 2).

Fig.5. The curves of recurrent periods (1) and amplitude frequency curves (2) of microtremors for various ground conditions. The figures correspond to the numbering of the observation points.

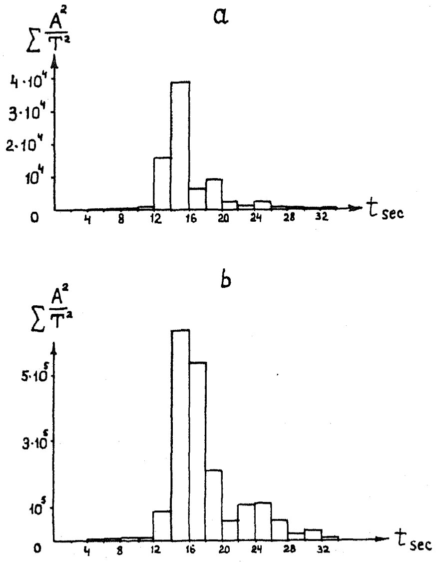

Fig. 1.

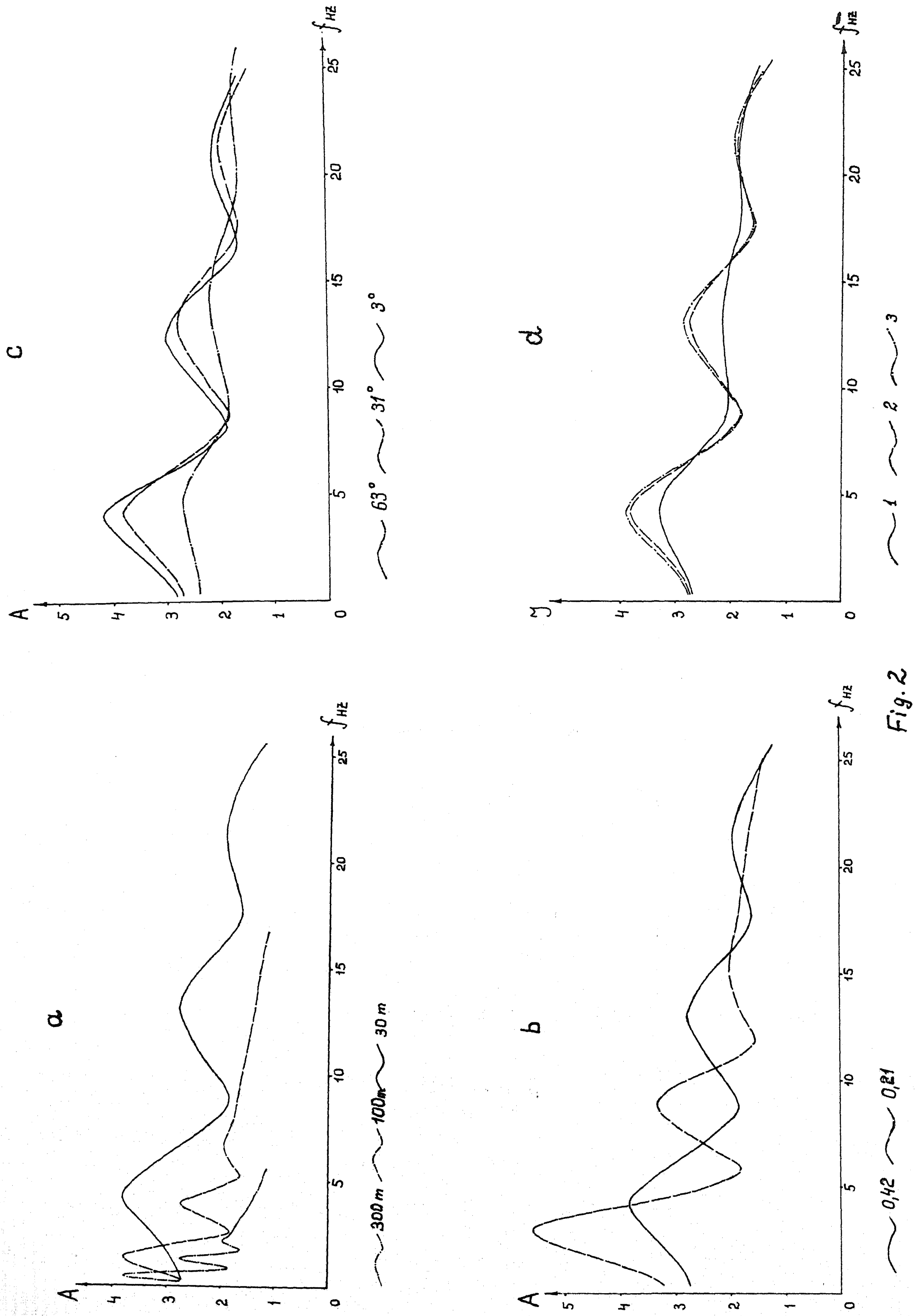

Fig. 2

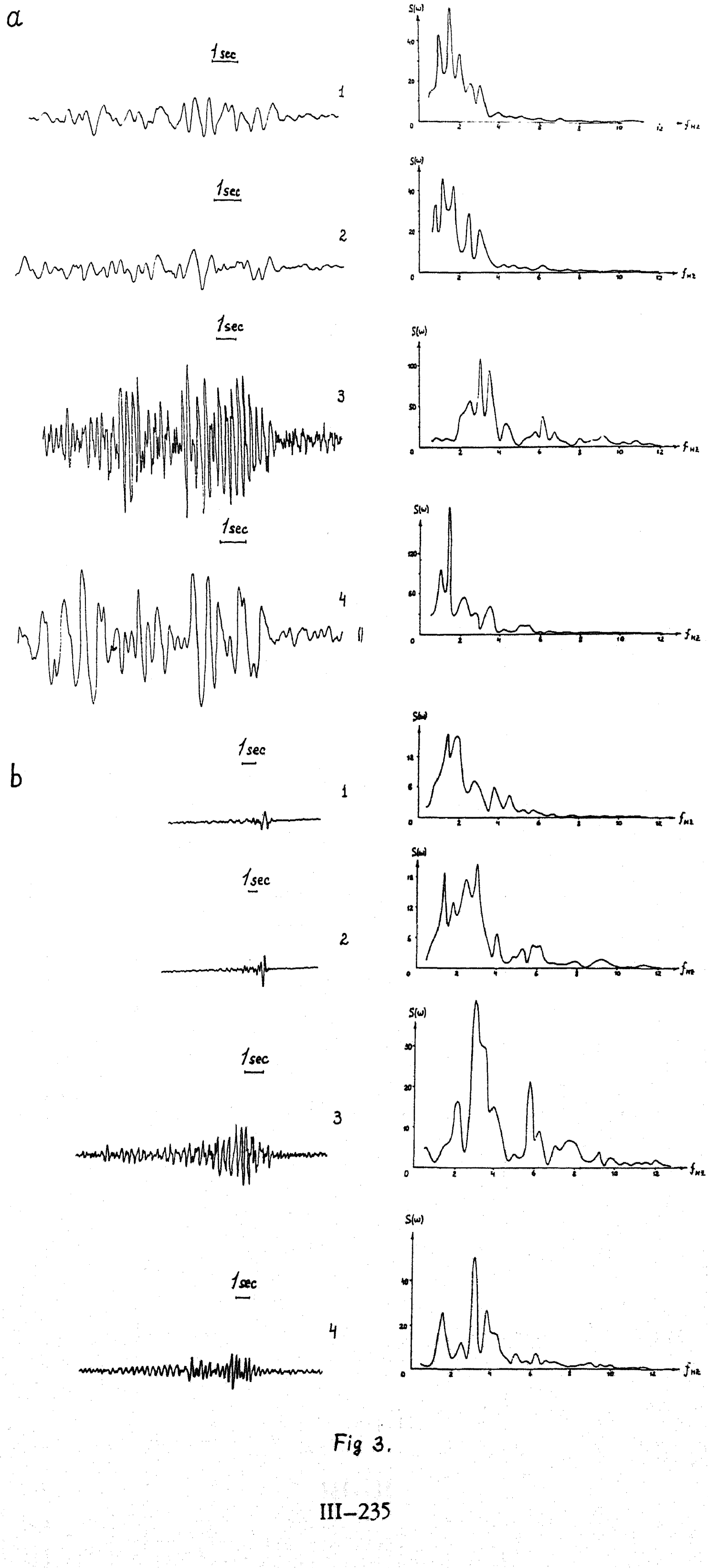

Fig 3.

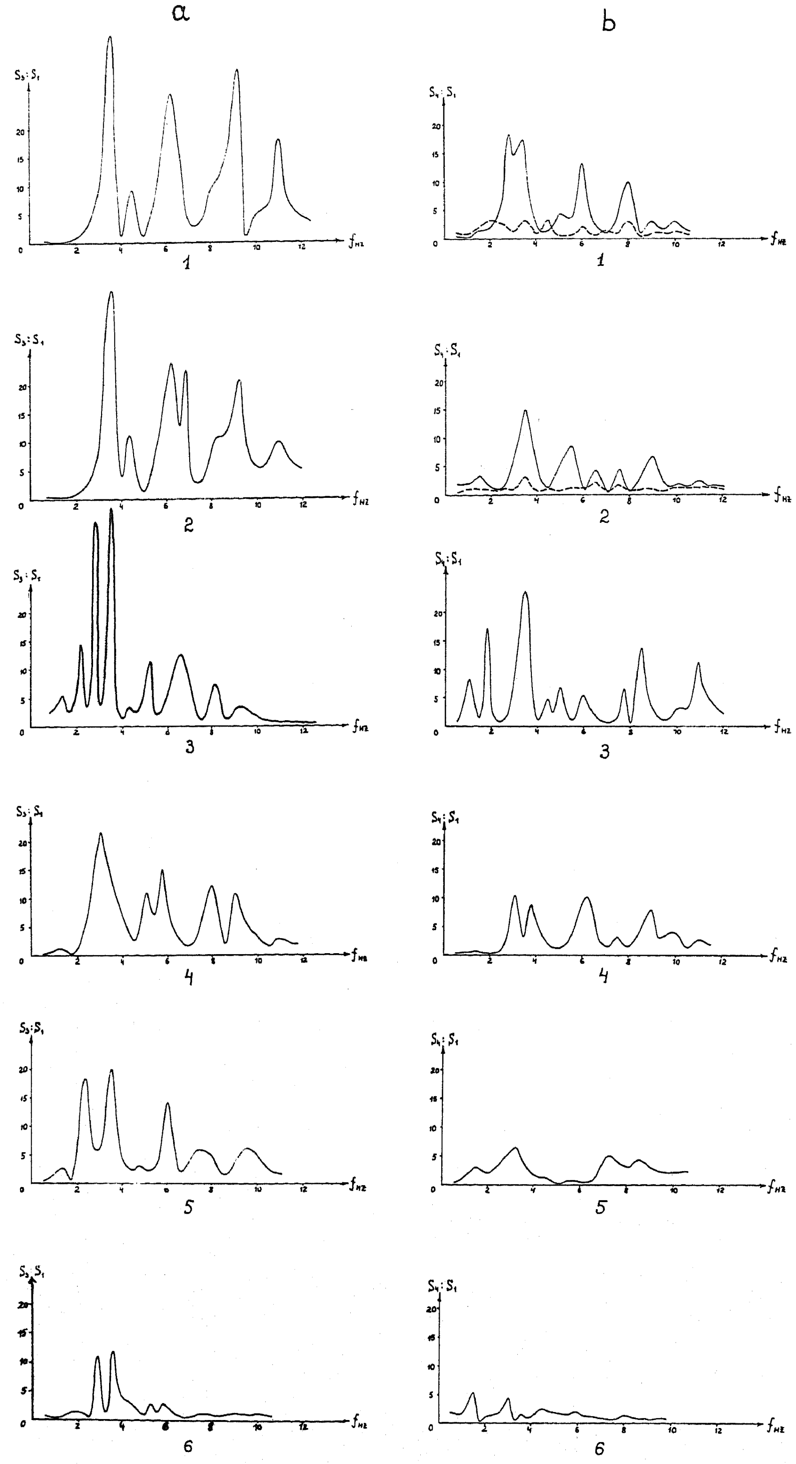

Fig 4.

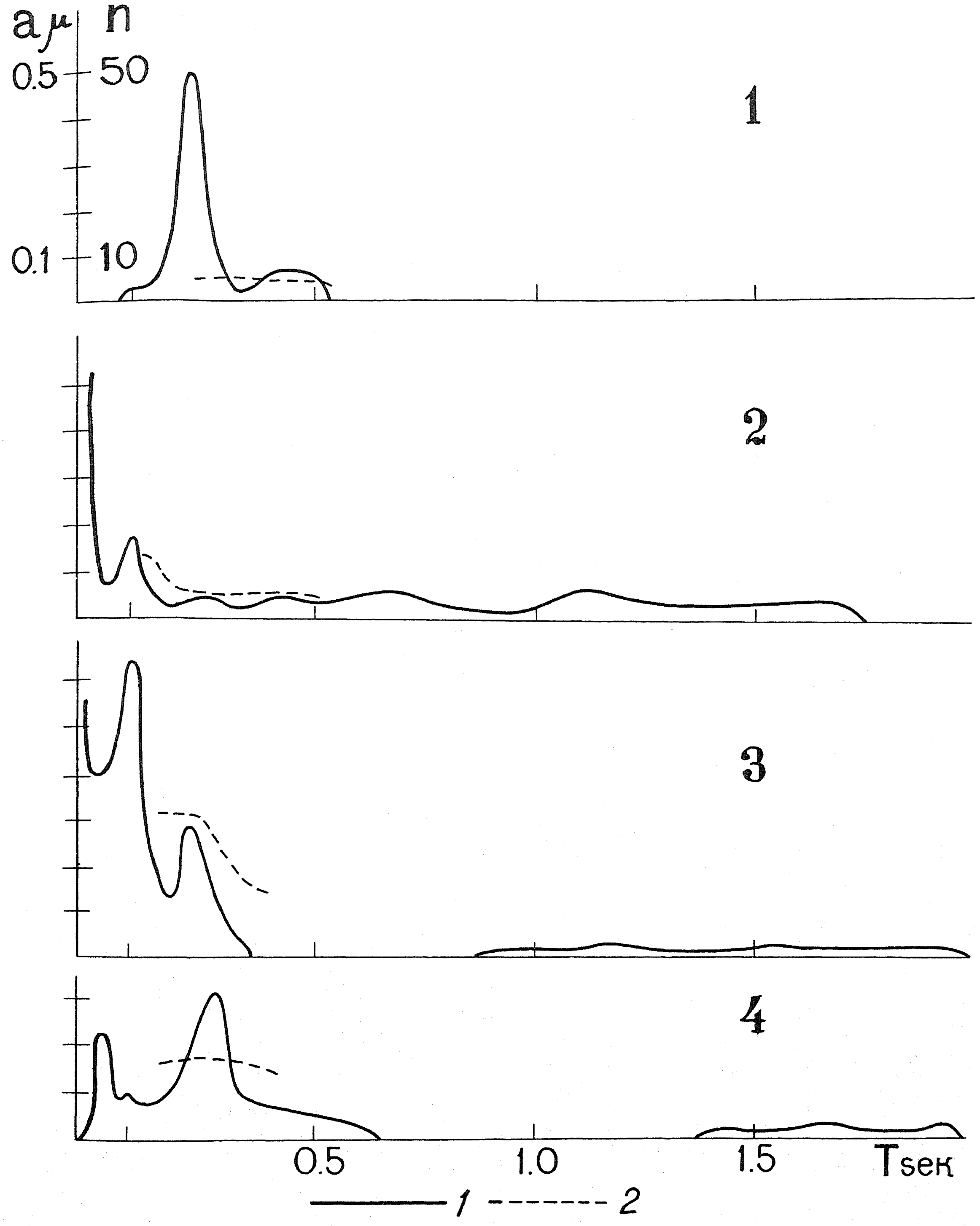

Fig 5