STUDIES ON THE SPECTRA OF GROUND VIBRATIONS CAUSED BY NEARBY EARTHQUAKES

by

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SYNOPSIS

This work evaluates the velocity spectrum[II)] of a strong earthquake which may occur in the region of Petropavlovsk Kamchatski. The spectrum of a strong earthquake ($M \approx 8.3$) is calculated on the basis of the analysis of velocity spectra of weak and average earthquakes the intensity not exceeding 6 III). The relation of velocity spectra of nearby earthquakes, of the territorial location, depths and distances is studied /2/. The effect of ground conditions on the vibration spectrum is considered. The seismograms were processed on electronic computers.

TERMS

M - magnitude;

E - earthquake energy, joule;

K - lg E. $K = 4,9 + 1,65 M$.

Δ - epicenter distance, kilometres;

H - depth of the earthquake focus, kilometres;

h - thickness of the ground layer, metres;

Φ_v - spectral density (spectrum ordinate);

v_s - average velocity of shear waves propagation in ground

C - constant;

f - frequency, cycles per second

f_{max} - frequency of the maximum of spectrum

α - degree of inclination of spectrum;

n - wave divergence index;

$\bar{\alpha}$ - waves absorption coefficient;

r - distance.

m - number of earthquakes in a group

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II) Fourier spectra; III) Earthquake intensity is evaluated in degrees of the seismic scale adopted in the USSR /1/

III) Intensity scale MM.

SEISMOLOGICAL CHARACTERISTIC OF THE REGION

The most probable place of occurence of focus of the earthquake with $M \approx 8.0$ is the place of outlet of the focal zone to the ocean bottom in front of the city of Petropavlovsk Kamchatski. The focal zone immerses westwards. The inclination angle is 50° /5,6/. The cluster of epicentres is stretching along eastern Kamchatka in a form of a strip parallel to the coast via the tips of Shipunsky and Kronotsky peninsulas. The western edge of this strip is 80-90 kilometres from Petropavlovsk Kamchatsky. All strong earthquakes in Kamchatka with $M \geqslant 8.0$ with the focal depth of 20-60 kilometres occur within the boundary of this strip. Such earthquakes, with epicentres not farther than 80-90 kilometres from the city can cause quakes forces up to 9 degree once in 200 years. Earthquakes of the same energy, with epicentres at a distance upto 150-200 kilometres can cause quakes with the force of 8 and 7 degree once in 80 and 40 years, respectively. There are no direct indications to the possibility of a strong earthquakes in immediate vicinity of the city /6/.

EARTHQUAKE SPECTRA OF DIFFERENT FOCAL ZONES

Fig.1 illustrates average velocity spectra of earthquakes in 4 focal zones. 1. Earthquakes in Kronotsky bay. Zhupanovsk earthquake with M = 7.0 (K = 16) and with the focal depth of 5-10 kilometres occured in this region on june 18, 1959. 2. Earthquakes on the Shipunsky peninsuly and its south-south-east continuation.This is the most active area within the boundaries of the East Kamchatka zone. Within this region there is located the epicentre of the earthquake occured on May 4, 1959, with M = 7.75, Δ = 110 kilometres and H = 20 kilometres, and which caused quakes of an average force of 7-8 degree in Petropavlovsk /5,7/ . 3. A group of earthquakes in Avachinsky bay. 4. Earthquakes with focus close to the city at depths of H 100 kilometres. Table 1 illustrates the parametres of focus of earthquakes and their spectral characteristics. The top boundary frequency, i.e. the frequency limiting the area in which 75 per cent of energy of the entire spectrum is concentrated, is shown in the last column. Now onwards we shall deal with vibration spectra of rocky ground.

Fig.1 and Table 1 indicate that when focus approaches Petropavlovsk Kamchatski, the spectrum extends to the high frequency region and its maximum also displaces to the high frequency region. But with the further approaching of the epicentre to the observation point the spectrum of earthquakes again becomes a low frequency one. The low frequency nature of the spectrum of a deep earthquake can be explained by the growth of the hypocentral distance. But the comparative analysis of the spectra of the individual earthquakes of the second and the fourth groups, having similar hypocentric distances, excludes this explanations. Thus, the low frequency nature of spectral of close to the city (Δ<50 kilometres), deep (H > I00 kilometres) earthquakes is probably explained by a strong absorption of the transverse waves in a layer of lower velocity at the depth of 80-I00 kilometres and deeper /2,8,9/. The dependence of a spectrum on focal depth within the limits of 5-I0 up to 60 kilometres is not noted.

EARTHQUAKE SPECTRA OF DIFFERENT ENERGY OF SOURCE.

I8 earthquakes with epicentric distances ranging from 85 to I20 kilometres and with a depth ranging from 20 to 60 kilometres were selected for analysing the dependence of a spectrum on thee energy of focus of earthquake. The earthquakes weredivided into three energy groups. Fig.2 illustrates average spectra of corresponding energy groups of earthquakes. The left-hand side (low frequency) and the right-hand side (the high frequency) branches of the spectra were approximated by straight line segments.

Graphs in Fig.2 ahow that as the energy of the focus of the earthquake is increased maximum of the spectrum is shifted into the region of low frequencies and the steepness of the decline of the high frequency branch of the spectrum into the region of high frequencies increases. The left-hand side and the right-hand side branches can be written approximately in an exponential form

$$\Phi_v' = C' \cdot e^{\alpha' f} \qquad f < f_{max}$$
$$\Phi_v = C \cdot e^{-\alpha f} \qquad f > f_{max} \qquad (I)$$

A clear dependence of α' on the energy value is not noticed for low frequency branches. The right-hand side branches of spectra I and 2 (Fig.2) can be approximated by a single straight line. The high frequency branch of the spectrum of the strongest earthquakes have to be approximated by two segments of a straight line having different inclination angle α .

Values of parameters of three groups of earthquakes and their spectral characteristics are given in Table 2. The average value and the interval for a probability of 0,9 are given in the last three columns.

Thus, we have established the nature of dependence of parameters of the amplitude-frequency spectrum of Kamchatka earthquakes on the energy of focus within the limit of I0-I4 grades of energy. If we assume that the spectrum of earthquakes of a higher energy grade is governed by the same law, then we can determine by the extrapolation method the values of those parameters for a higher energy grade by plotting parameters of spectrum Φ_{max} (the level of the maximum of spectrum), f_{max}, α depending on the energy.

The graphs of relations of $\Phi_{max} = \varphi$ (K), $f_{max} = \psi$ (k), and $\alpha = \zeta$ (k) are shown in Fig.3. Here the inclination of the first (low frequency) component of the right-hand branch of the spectrun is designated through for the third group spectrum. The points of the graph are not on one straight line as it is seen from Fig.3. The least scattering is characteristic of the graph f_{max}.

In drawing straight lines we tried to determine parameters of the spectrum of an earthquake of the I6-th energy grade ($M \approx 7.0$). The spectrum of earthquake obtained through calculations is shown in Fig.2 by a dotted line. Let us compare the spectrum calculated by us with the velocity spectra of some earthquakes of the Pacific Ocean zone. The calculated spectrum and the spectrum of the group of the strongest recorded earthquakes with K = I3-I4 which are brought to one and the same level are shown in Fig.4. Below is the spectrum of the earthquake which occured in Japan on February I5, I956, and spectra of six California earthquakes (indices 2-8). Earthquakes with M = 6.0-7.0, $\Delta \approx$ 60-I30 kilometres were selected. The intensity of quakes reached 7-8 degree at the registration site.

It is possible to draw the following conclusions by comparing the calculated spectrum with the spectra of earthquakes in the Pacific Ocean zone whose parameters M, Δ and H are close to the parameters of the rated earthquake:

I. The position of the maximum of the calculated spectrum I-b (Fig.6) and of the spectra of strong earthquakes in the Pacific Ocean zone are approximately the same, i.e. $f_{max} \approx$ I cps .

2. A steep decline in the similar frequency range is the characteristic feature of all the spectra under consideration.

3. The steepness of decline of the calculated spectrum and of the spectra of the Pacific Ocean zone earthquakes are also very close. But in some cases it is difficult to approximate by a single segment of a straight line the high frequency branch of spectra of strong earthquakes.

From the analysis of the spectra in Fig.2 we see that if the right-hand side curve of the calculated spectrum is prolonged into the region of high frequencies, at frequencies of about 7 cps the energy of vibrations during the earthquake with K = I6 is equal to the energy of vibrations of earthquakes with K = I3-I4, and for frequency exceeding 7 cps it is smaller than the latter. The analysis of damages caused by strong earthquakes does not confirm it.

Thus, the position of the maximum of the calculated spectrum and the steepness of its high frequency curve in its initial part (in the region of low frequencies) corresponds evidently to the truth. But the available data do not make it possible to plot a full-calculated spectrum, for the position of the cleavage points is not clear and the inclination angle of the second component of the high frequency branch of the spectrum is not known.

That is why in further calculations for the spectrum of a strong earthquake we shall adopt a conditional spectrum, whose form is similar to that of spectrum 3 (Fig.4) but is displaced in a due way with respect to the ordinate and the frequency. The spectrum of velocity of an earthquake of the I8-th energy grade, plotted by such method, is shown in Fig.5 by solid line /2/.

VARIATION OF VIBRATION SPECTRUM DEPENDING ON DISTANCE

The spectrum of a strong earthquake was calculated on the analysis of spectra of Kamchatka earthquakes with epicentric distance equal on the average to I00 kilometres. That is why the calculated spectrum should be referred to this value of epicentric distance. It was earlier pointed out to a possible occurence of a strong earthquake with K = I8 ($M \approx 8.3$) at a distance of Δ = 80 kilometres.

It is necessary to define the damping parameters of seismic waves depending on distance in order to solve the problem of determining the spectrum of vibrations at a fixed distance r. We compare the energy spectra of three groups of earthquakes with Δ = 90 kilometres, 150 km and 250 kilometres to determine the damping parameters. Those spectral curves are given in Fig.6.

The absorption coefficient $\bar{\alpha}$ which turned out to be linked with the frequency of linear relationship

$$\bar{\alpha} = 0{,}003 \cdot f \cdot km^{-1} \qquad (2)$$

was determined by the divergence of spectral curves.Then the problem was reduced to determining the level and the form of the spectrum of earthquakes with K = I8 at a distance of Δ = 80 kilometres by the initial spectrum, detrmined for the distance of Δ = IOO kilometres. The ordinates of unknown spectra Φ_{r_2} are calculated through the known ordinates of spectra Φ_{r_1} by means of the following ratio

$$\Phi_{r_2} = \Phi_{r_1} \cdot \frac{e^{1/2\bar{\alpha}(f)\cdot r_1}}{e^{1/2\bar{\alpha}(f)\cdot r_2}} \cdot \left(\frac{r_1}{r_2}\right)^{n/2} \qquad (3)$$

The abporption value $\bar{\alpha}$ is known. The divergence index n is assumed to be 2.8. The calculated spectrum is shown by a dotted line in Fig.5 /2/.

EFFECT OF GROUND CONDITIONS ON VIBRATIONS SPECTRUM

The analysis of the May 4, I959, earthquake showed that the buildings in the city had different damages depending on the ground conditions. Soft flooded alluvial deposits of intermountain hollows and river valleys, and man-made ground of the coastal strip, where the intensity of vibrations reached 8-9 degree turned out to be the worst from the seismic point of view. The intensity reached 7 on the surface of thick (h>IOO metres) dry volcanic depossits. Quakes with a force of 6 degree were registered on volcanic solid rock /7/.

Seven seismical stations were installed in the city at places with different but typical for the given region types of ground. The station installed on the surface of monolith rocky ground was chosen as the master one. Data of other seismic stations were compared to the data obtained by the master station.

Spectra of velocity of ground vibrations at the observation sites I-7 are shown in Fig.7.

It is seen from Fig.7 that the vibration spectra at sites I,2 and 7 which were located on close by nature rocky and semi-rocky grounds (gabbrodiabase, sand-clay and siliceous shales) resemble each other. A rather smooth decline into the region of high frequencies and the absence of sharp maxima and minima on the spectral curve is a characteristic feature of them. The vibrations spectra on the surfaces of the pebble rocks and sandy-loamy soft formations (sites 3-6) have a higher level on the ordinate practically throughout the entire frequency range, which is of interest to us, and one or several sufficiently clear maxima and minima /IO/.

Spectral characteristics of geological sections in sites 2-7, obtained by dividing spectra in appropriate sites by the vibration spectrum in site I, are given in Fig.8. But those spectral characteristics correspond to individual sections and have another form if the geological section is changed. Generalized spectral characteristics were plotted. The territory of the city was divided into several zones. Each zone is characterized by a definite, rather wide range of ground sections. A spectral characteristic of each zone is enveloping of all possible spectral characteristics corresponding to individual sections of this zone. Spectral characteristics of sections were calculated on electronic computers / 4/. Spectral characteristics of 6 ground complexes chosen on the Petropavlovsk Kamchatski territory are given in Fig.9.

Spectra of vibrations velocity are determined for every zone by the multiplying of appropriate spectral characteristic $K_i(f)$ by the calculated spectrum of a strong earthquake $\Phi_1(f)$. Spectrum $\Phi_1(f)$ was calculated for site I.

$$\Phi_i(f) = \Phi_1(f) \cdot K_i(f) \tag{4}$$

where i - is the number of the corresponding zone (I-YI).

The spectra of vibrations velocity of ground caused by a strong earthquake with $M \approx 8.3$, which is possible in the given region, are shown in Fig.IO.

The spectral method , suggested in the work, makes it possible to more reasonably approach to the designing and calculation of buildings fit for seismic force under the condition of the given region.

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Table I

No.s	K	H,km	km	f_{max} cps	f cps
I	IO-I4	0-I00	I20-I70	I.6	4.9
2	IO-I4	0-I00	85-I05	4.3	5.6
3	IO-I2	30-I00	55- 65	2.2:5.5	6.I
4	IO-I2	I00	I8- 45	I.9	4.8

Table 2

No.s	m	K	H,km	Δ, km	f_{max} cps	Φ_{max}	α
I	7	IO-II	20-60	85-I20	2,2±0,46	0,079± 0,028	0,28± 0,I2
2	IO	I2-I3	20-60	85-I20	I.87± 0.25	0.50± 0.I7	0.34± 0.005
3	3	I3-I4	20-60	85-I20	I.55 (I.4-I.65)	I.I0 (0.74-I.60)	0.50 (0.43-0.57)
							0.I6 (0.I4-0.I9)

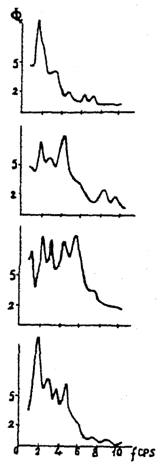

FIG.I. EARTHQUAKE SPECTRA OF DIFFERENT SEISMIC ZONES. I - KRONOTSKY BAY. 2 - SHIPUNSKY PENINSULA. 3 - AVACHINSKY BAY. 4 - PETROPAVLOVSK-KAMCHATSKI AREA.

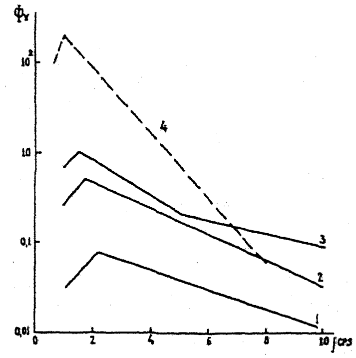

FIG.2. VELOCITY SPECTRA OF EARTHQUAKES OF DIFFERENT ENERGY. I.K=IO-II. 2.K=I2-I3. 3.K=I3-I4. 4.K=I6 (CALCULATED SPECTRUM).

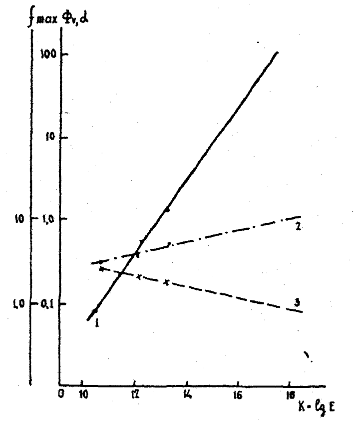

FIG.3. GRAPHS OF RELATIONSHIPS OF PARAMETERS OF EARTHQUAKE SPECTRUM AND SEISMIC SOURCE ENERGY. I. $\Phi_{max} = \varphi(K)$. 2. $\alpha = \xi(K)$. 4. $f_{max} = \Psi(K)$.

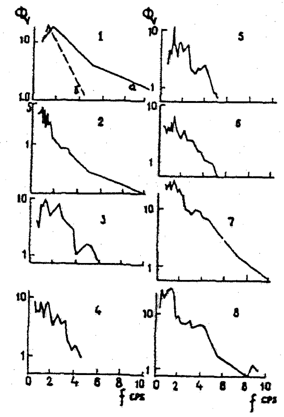

FIG.4. SPECTRA OF STRONG EARTHQUAKES OF THE PACIFIC OCEAN ZONE.

Ia. SPECTRUM OF SENSIBLE KAMCHATKA EARTHQUAKES K=I3-I4.

Ib. CALCULATED SPECTRUM K=I6.

2. SPECTRUM OF EARTHQUAKE IN JAPAN.

3-8. SPECTRA OF EARTHQUAKES IN CALIFORNIA.

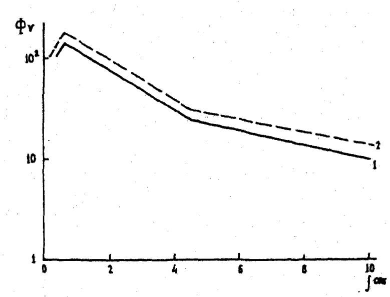

FIG.5. CALCULATED SPECTRA OF VIBRATION VELOCITY OF ROCKY GROUND CAUSED BY EARTHQUAKES WITH $M \simeq 8.3$. I.Δ= IOO kilometres. 2. Δ= 80 kilometres.

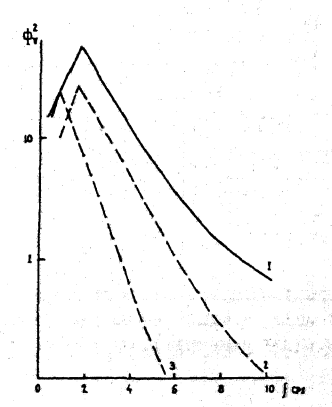

FIG.6. SPECTRA OF EARTHQUAKES OF I2-I3 GRADES OF ENERGY WITH DIFFERENT EPICENTRAL DISTANCES. I.Δ = 90 kilometres. 2.Δ = I50 kilometres. 3.Δ = 250 kilometres.

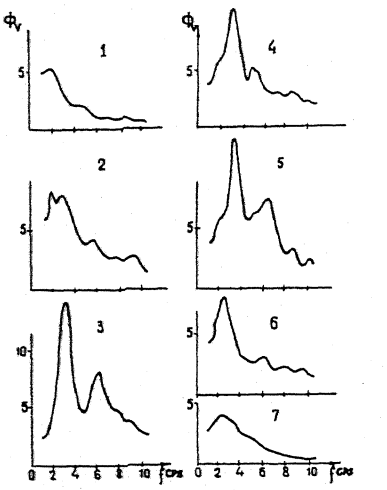

FIG.7. SPECTRA OF GROUND VIBRATIONS VELOCITY AT I-7 OBSERVATION POINTS.

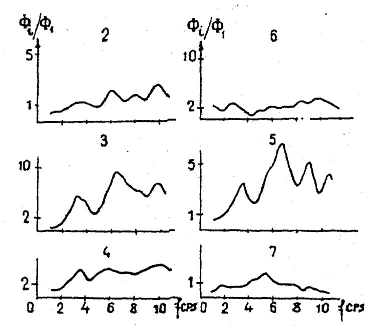

FIG.8. SPECRTAL CHARACTERISTICS OF MEDIA IN OBSERVATION POINTS 2-7, WITH RESPECT TO MASTER POINT I.

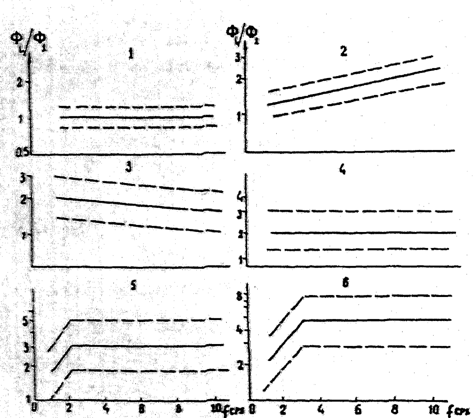

FIG.9. SPECTRAL CHARACTERISTICS OF SIX GROUND COMPLEXES, SINGLED OUT ON THE PETROPAVLOVSK KAMCHATSKI CITY TERRITORY.

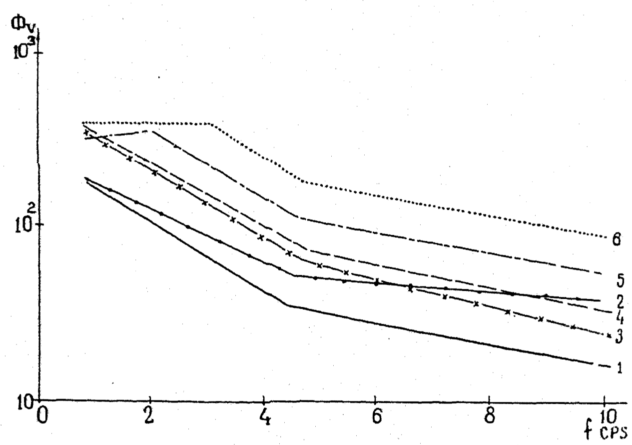

FIG.IO. SPECTRA OF VIBRATIONS VELOCITY OF EARTHQUAKES WITH $M \approx 8.3$ FOR SIX ZONES WITH DIFFERENT GROUND CONDITIONS.

I. MONOLITH ROCK AND SLIGHTLY CRACKED ROCKY GROUND V_s= I200-I300 metres per second.

2. ROCKY GROUND DAMAGED ON THE SURFACE. V_s= 800-I200 metres per second.

3. THICK (h > 200 metres) SOFT PYROCLASTIC AND DETRITUS-SHINGLE DEPOSITS (h>IOO metres).

4. SOFT PYROCLASTIC DEPOSITS WHOSE THICKNESS RANGES FROM 70 to 200 metres AND BOULDERY-PEBBLED ROCKS WHOSE THICKNESS RANGES FROM I5-20 to IOO metres. V_s = 500-600 metres per second.

5. SOFT PYROCLASTIC DEPOSITS WHOSE THICKNESS RANGES FROM IO TO 70-80 metres. V_s= 400-500 metres per second.

6. VERY SOFT PYROCLASTIC DEPOSITS AND ARTIFICIAL SILT AND ALLUVION GROUNDS WITH A THICKNESS RANGING FROM 4 TO 25-30 metres. V_s<400 metres per second.