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Polarization characteristics of vibroseismic field

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In the article, there resumed the results of polarization treatment of seismic fields from various types of powerful vibrators depending on temperature of surrounding air. Peculiarities of P- and S-waves in these conditions have been studied.

Polarization method of wave fields analysis in accordance with high-resolution vibroseismic method of the Earth's sounding may enormously expand possibilities of studying seismic fields thin three-dimensional structure in connection with various geodinamic processes analysis.

Such correspondence of both methods is provided due to the using of seismic vibrators with high metrological force and frequency-timing characteristics. At present, there achieved precision of supporting amplitude of vibrations not worse than 5%, frequency $10^{-5} \div 10^{-6}$, phase $\pm(1 \div 1.5)$ degree, setting up the moments of starting the sounding processes with error not worse ± 1 ms. Thanks to such high indexes of seismic waves sources high accuracy of measuring wave field parameters in a remote zone at hundreds kilometers distances is achieved. The demand far providing measurements of high accuracy is necessary for revealing and control of various geodinamic processes, which develop in areas of coming earthquakes, landslides, volcano explosions and so on.

The essence of polarizational method consists in studying time-space characteristics of wave fields and, therefore, apparently, this method is the most adequate to the tasks of studying thin parameters of environment geodinamics.

Realization of this method is connected with applying spatial system of observation, consisting of 3-components seismoreceivers and with performing three-dimentional interpretation of observation results. Polarization characteristics of seismic fields measured with the help of such system to great extent depends on disturbing power polarization in vibrator itself. Deep seismic sounding of the Earth with the help of powerful vibrators has some peculiarities in comparison with traditionally used explosions. In particular, there is a possibility of using the mode of monochromatic oscillations which allows essential raising of ware field parameters measuring accuracy, and first of all, its field amplitudes $\{A_x^*, A_y^*, A_z^*\}$ and phases $\{\varphi_x^*, \varphi_y^*, \varphi_z^*\}$. Solving a number of tasks of vibration seismic [1, 2] aims at using these parameters.

The purpose of this paper is to put the results of measurings and analysis of wave fields polarization characteristics peculiarities created by powerful lowfrequency vibrators of types CV-100, CV-40, HRV-50 at distances up to 430 km. Such fields registration has been done with the help of space-distributed 3-components seismoreceivers SK1-P included into complexes of registration and processing vibroseismic signals VIRS [3], KROSS-PC [4]. Characteristics of seismoreceivers geometric arrangement will be additionally mentioned in the paper in connection with concrete registration points.

Let us introduce some definitions. Seismic waves polarization stands for trajectory of vectors, describing seismic vibrations in coordinates of registered components X, Y, Z. Under vibration polarogram or just polarogram we mean the trajectory of vibration seismogram polarization vector obtained at components X, Y, Z. As it is known, the latter is calculated as a result of convolution in the form

$$R(i) = \frac{1}{N-i} \sum_{j=0}^{N-i-1} U(j) \cdot S(j+i), \qquad i = 1, \ldots, m,$$

where $U(j)$ is registered seismic signal, $S(j)$ is base signal, restored at the registration point in the form of sounding signal copy.

The tasks of numerous experimental material analysis are as follows:

- representation of wave fields of distant space-distributed vibrators with the help of compact areas $V_1, \ldots, V_m$ in the space $\{X, Y, Z\}$ and determination of compactness numeric characteristics. Obviously, such reflection is necessary for the task of sources types classification;
- estimation of quantitative characteristics of P- and S-waves (polarograms) depending on the sources types and also of acoustic waves that under certain conditions accompany seismic waves [5];
- determination of arrival direction and expansion velocity of seismic waves;
- estimation of polarogram parameters variations in connection with the Earth rising tides.

Let us consider the brief characteristic of the results of analysis concerning all the questions mentioned above.

Characteristics of wave fields parameters of three-dimentional reflection. Considering numerous sounding performances in monochromatic mode of vibrations for the given pair of excitement and registration the components of the full vibrations vector $\{A_x^*, A_y^*, A_z^*\}$ and phases φ_x^*, φ_y^*, φ_z^*, have been measured.

The parameters given correspond to amplitudes and initial phases of set harmonic oscillations on components X, Y, Z that have been registered at

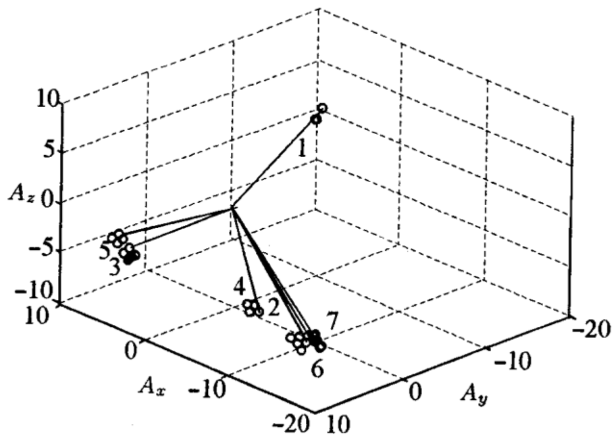

Figure 1

a remote receiving point. Obviously their values will depend on amplitudes and initial phases of vibrations $S(t)$ at the source:

$$S_{il}(t) = A_{il}\cos(\omega_0 + \varphi_{il}), \qquad i = 1, \dots, N, \quad l = 1, \dots, L.$$

The index i determines the value of amplitude and initial phase of oscillations of the source; L is the number of sounding performances sets. It is possible to imitate the work of spatially-distributed sources for each from L sets by giving, in particular, fixed φ_i. Figure 1 presents the vectors $\{A_x^*, A_y^*, A_z^*\}$ of 39 repeating sounding performances, measured at a point removed on 430 km from vibrator CV-100. Compactness of reflection areas $V_1, \dots, V_m$ is estimated by vector values dispersion with regard to mean vector and defined as

$$\delta_m = \frac{1}{N}\sum_i^N\sum_j^N |\bar{A}_i - \bar{A}_j|.$$

The values of compactness measure for the areas $V_1, \dots, V_m$, calculated for repeating sounding performances and $N = 3 \div 8$ are presented below.

area	V_1	V_2	V_3	V_4	V_5	V_6	V_7
Δr	1.50	1.10	1.71	0.47	1.41	1.98	0.97
r	12.37	16.98	9.67	7.65	8.81	16.44	17.21
$\Delta r/r$	0.12	0.06	0.17	0.06	0.16	0.12	0.05

As one can see, relative error of reflection does not exceed 10%. That testifies high stability of characteristics of the circuit: radiator-environment-receiver under the condition of high-resolving timing synchronization of sounding and registered oscillations. The result obtained may be taken as a basis of sources types classification on the grounds of using images identifying algorithms.

Quantitative characteristics of wave polarogram of P- and S-waves from various types of vibrators. There have been constructed and analyzed polarogram from the sources of the types CV-100, CV-40 through numerous sounding performances, executed on traces 50, 320, 355 km length. At the same time polarogram peculiarities of seismic (P, S) and acoustic waves have been studied. Under certain conditions the latter may be registered at long distances from vibrators simultaneously with seismic waves [5]. Polarograms analysis has been performed in the coordinates $\{X, Y, Z\}$, $\{X, Z\}$, $\{X, Y\}$, $\{Y, Z\}$, bounded to the observation point and also within spatially-distributed system of observation $\{Z_1, Z_2, \ldots, Z_5\}, \{Y_1, Y_2, \ldots, Y_5\}$, $\{X_1, X_2, \ldots, X_5\}$.

As an example, in Figure 2, the waves polarograms in coordinates X, Y, Z are presented. These waves were isolated on vibration seismograms obtained at the distance of 355 km from the source on 5 receivers, which had been placed along the linear profile with 200 m intervals. Dispersion figure represented polarogram of P-wave is an ellipsoid in a three-dimentional or ellipse in a two-dimentional spaces. For quantitative characteristics of polarogram features there are calculated correlation coefficient estimations between the components R_x^*, R_y^*, R_z^* of the full oscillation vector

$$\frac{r_{xy}\operatorname{cov}(X, Y)}{\sigma_x\sigma_y}, \qquad \frac{r_{xz}\operatorname{cov}(X, Z)}{\sigma_x\sigma_z}, \qquad \frac{r_{zy}\operatorname{cov}(Z, Y)}{\sigma_z\sigma_y}, \tag{1}$$

where σ_x, σ_y, σ_z are selective meansquare meanings of the values R_x^*, R_y^*, R_z^* accordingly; $\operatorname{cov}(X, Y) = \frac{1}{N}\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})$ is a covariation between discrete counts of the vibration seismogram R_x^*, R_y^*. Obviously, the higher is r coefficient, the more compact the dispersion figure is concentrating along the big axis of the ellipse at a limit (when $r = 1$) coming to a line. Thus with the help of r it is possible to characterize the degree of linearity of connection between the components of the oscillation vector R. Inclination angle of ellipse big axis is calculated in the following form:

$$\Theta_{zx} = \frac{\sigma_z}{\sigma_x}\operatorname{arctg} r_{zx}. \tag{2}$$

On the basis of given relations there have been calculated meanings coefficient correlation of polarograms for various types of seismic and acoustic waves. Along with that the type of vibrator, distance of sounding, and the season were taken into consideration.

At a distance of 50 km vibrosounding performances were carried out in April–December 1996 with the help of vibrators CV-100, CV-40 in frequency range $6.25 \div 9.57$ Hz during 47 min scanning. Registration was carried out with the help of 3-components seismoreceiver of the type SK1-P, which component X was oriented towards the source. Polarograms analysis was carried

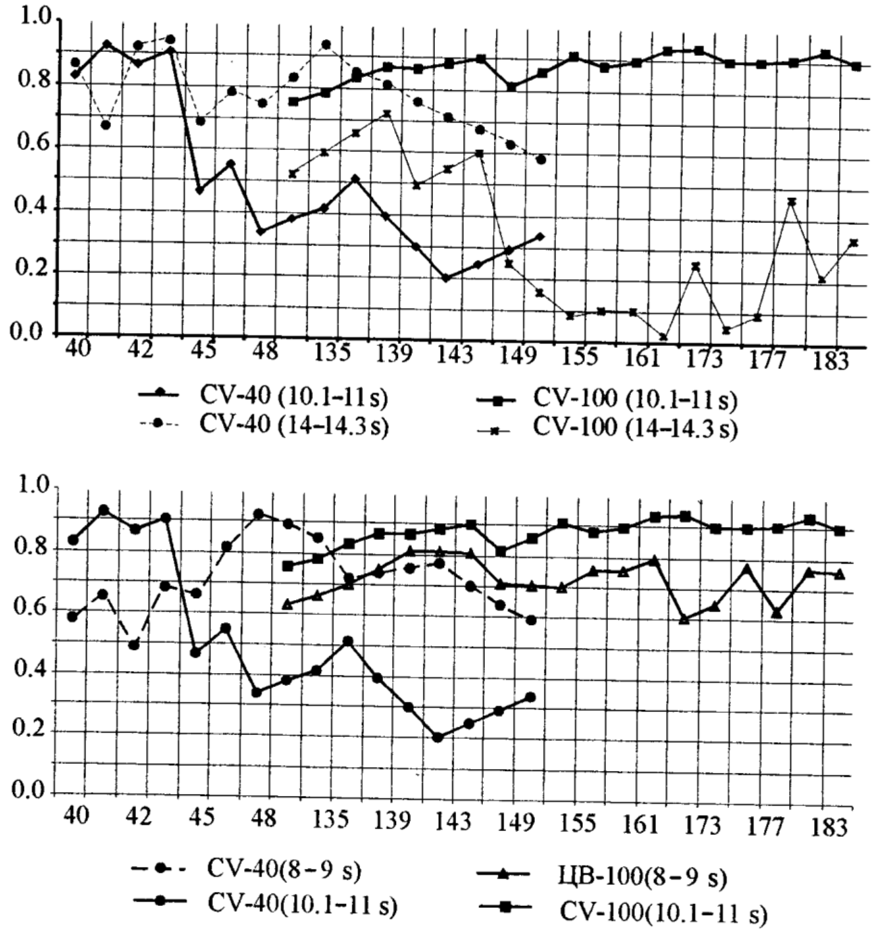

Figure 2. Correlation coefficients of Z and Y components for vibrators CV-40 and CV-100

out at 4 time-intervals: 1) arrival of P-wave at 8–9 s, 2) arrival of powerful reflected wave at 10–11 s, 3) arrival of S-wave at 14–15 s, 4) arrival of acoustic wave at 147–154 s. The highest correlation coefficient meanings for seismic waves were obtained at coordinates $\{Y, Z\}$, therefore in Figures 2a, 2b there are given the calculation r_{zy} on numerous sounding performances at selected intervals.

Let us consider the brief analysis of the data obtained:

First interval (arrival of P-wave). With respect to vibrator CV-100 r_{zy} meanings are in limits 0.63–0.8 (see Figure 2a) and practically do not depend on the temperature of ground surface layer under the source. The temperature of surrounding air was changing in limits $1.5 \div 25$ degrees during all sounding performances. With respect to vibrator CV-40 r_{zy} increases from 0.5 to 0.9 (see Figure 2b) with surface layer melting and then decreases again up to 0.6 with its freezing.

Second interval (arrival of powerful reflected wave). In this interval one can observe the highest meanings of $r_{zy} = 0.75$–94 with respect to vibrator CV-100, moreover coefficient increasing occurs with surrounding air temperature decreasing from +10 degrees up to -25 degrees, and accordingly with ground surface layer freezing (see Figure 2a). Mean values of r_{zy} are 0.88 here.

On the contrary with respect of r_{zy} to vibrator CV-40 one can observe an enormous values overfall of r_{zy} from 0.87 (frozen ground in performances 40–43) up to 0.2 (heated ground). It is clearly seen in Figure 2a.

Third interval (arrival of S-wave). Here, with respect to vibrator CV-100, one may observe a sharp abatement of r_{zy} from 0.6–0.7 up to 0.1 with ground freezing. For the interval considered $\bar{r}_{xy} = 0.28$. On the contrary for vibrator CV-40 high values of $r_{zy} = 0.6$–0.9 and $r_{zy} = 0.8$ were obtained. Tendency towards values abatement of r_{zy} with ground freezing under the vibrator reveals itself by analogy with the former case (see Figure 2a).

Forth interval (arrival of acoustic of S-wave). On the analogy with the previous case there remains a tendency towards r_{zy} values decreasing from $0.6 \div 0.9$ up to 0.1 with the Earth surface layer temperature lowering (Figure 3). Here such coefficient values of r_{zy} may be considerably higher than for seismic waves. As an example polarograms of seismic S-wave and acoustic wave are presented in Figure 4. From this figure we can see that the acoustic wave (b), (d) is characterized by considerably higher polarogram compactness and therefore, by higher correlation coefficient.

At a distance of 355 km regular soundings were carried out by sweep signals in frequency range of 5.469–8.496 Hz during 43 min 12 s. Registration of signals was carried out with the help of line consisting of 5 seismoreceivers, placed along the profile of 800 m length with 200 m intervals. The profile was oriented towards the source. Every component of X seismoreceivers

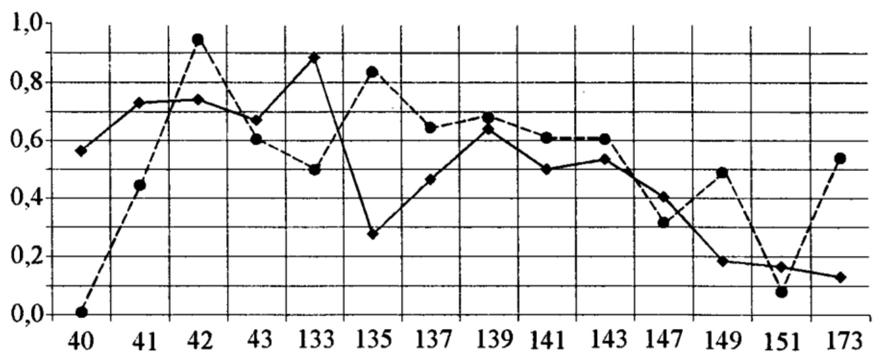

Figure 3. Correlation coefficients of $X : Z$ (—◆—) and $Y : Z$ (-●-) components on time interval of acoustic wave

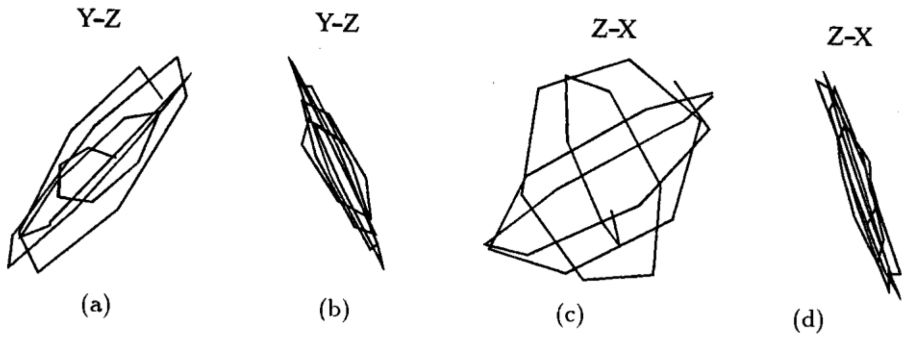

Figure 4. Polarograms (a), (c) of seismic S-wave at 14.5–15.0 s and (b), (d) acoustic wave at 147.5–148.0 s

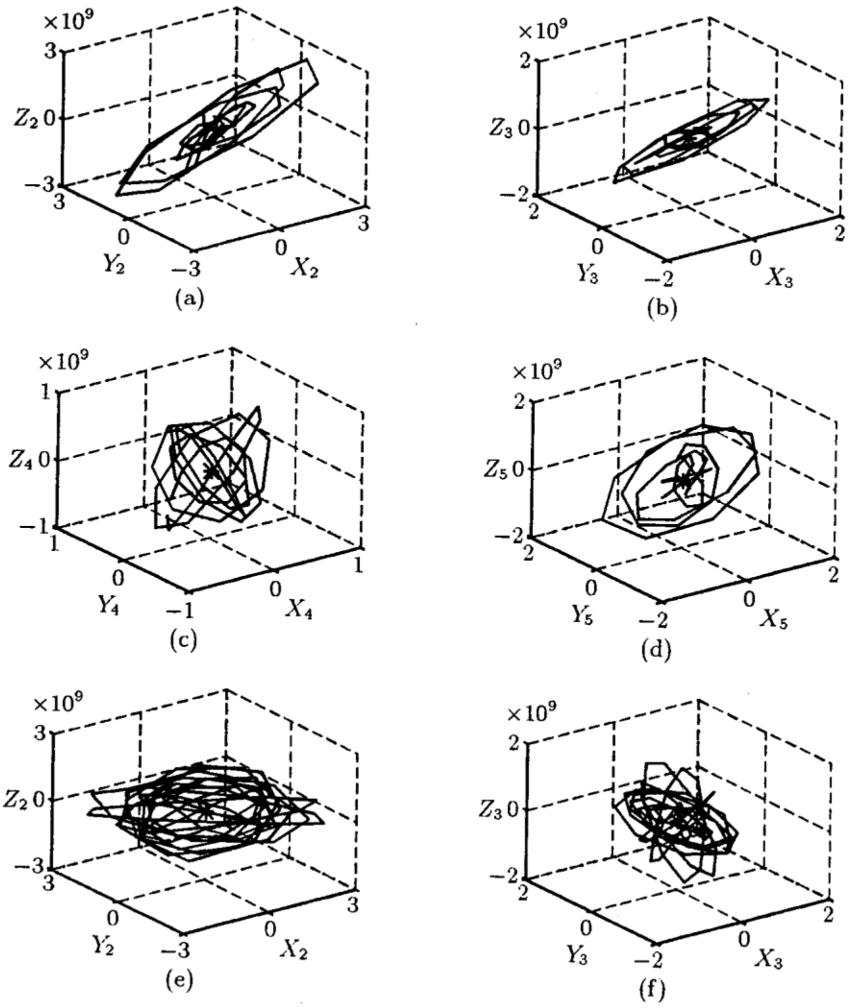

Figure 5. Polarograms (a)–(d) of P-waves and (e),(f) S-wave

was oriented in the same direction. On the basis of polarization analysis of wave field along the registration profile one can initially see that polarization character fluctuates from receiver to receiver. This concerns P-waves and especially S-waves. As an illustration in Figure 5 there are presented P-waves polarograms in coordinates X, Y, Z on 4 adjacent receivers (a), (b), (c), (d). Below there are presented polarograms of S-waves at 2 adjacent receivers (e), (f).

The highest correlation coefficient values ($0.4 \div 0.6$) were obtained at coordinates $\{X_1, Z_1, \dots X_5, Z_5\}$ for P-wave. Mean value of coefficient was equal to 0.5. On other components mean values $\bar{r}_{xy} = 0.25$, $\bar{r}_{zy} = 0.34$ were obtained.

The main features of considered waves polarograms reveal themselves in:

- high degree of components Z, Y correlation from vibrator CV-100 at intervals of arrival of P-wave and considerably lower degree for S-wave. This divergence increases especially strongly with ground freezing under vibrator. On the basis of this indication it is possible to separate P- and S-waves from the given source type;
- differences with respect to 2 types of sources CV-100 and CV-40, revealing themselves in higher correlation of components Z, Y for S-wave, created by vibrator CV-40 in comparison with vibrator CV-100. In the first case during sounding performances mean value of r_{zy} was 0.8, in the second – 0.28. The first difference is more stable in comparison with the second one with surface layer temperature variation under vibrator;
- sharp decreasing of components Z, Y correlation coefficient at the interval of S-wave, created by vibrator CV-100 with freezing of surface layer under vibrator;
- the highest and most stable coefficient values of r_{zy} at the interval of strongly expressed reflected wave from vibrator CV-100, following after P-wave. Obviously, such wave may be used as a distinctive sign with respect to the given source type;
- decreasing of coefficients values of components correlation at large distances from vibrator. The highest values at a distance of 355 km were obtained in coordinates $\{X, Z\}$ for P-wave and were equal in average to 0.5.

Conclusion

On the basis of the experimental measurements data the peculiarities of seismic waves polarization characteristics first of all, of P- and S-waves from various types of powerful vibrators (CV-100, CV-40) have been analyzed.