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Dynamic characteristics of wave fields in fractured and fluid-saturated media*

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Abstract. In this paper, to solve the problem of active vibroseismic monitoring of the processes of fracturing and dilatancy in seismic- and volcano-prone zones, we take into account the dynamic characteristics of the wave field, in addition to a tracking change in the coefficients of medium anisotropy and propagation velocities of P- and S-waves earlier proposed by A.S. Alekseev. Thereby, the waveform variations and nonlinear transformation of wave fields associated with the geodynamic processes developing in destruction source zones will be taken into account. The efficiency of the approach proposed was confirmed by the results of experimental investigations with the method of vibrational sounding of mud volcanoes of the Taman mud volcano province and the tectonic fracture in the Novosibirsk region. The problem of estimating the dynamics of geodynamic processes in the destruction source zone becomes a multiparametric problem, which can be solved by the pattern recognition methods.

1. Introduction

Seismic heterogeneity of the Earth's crust is its important property. It is typical of many Earth's crust zones: preparation zones of natural disasters (earthquakes and volcano eruptions), fracture zones, etc. This type of heterogeneity is characterized by local inhomogeneities with different geometric parameters, contrasts, structural organization, and distribution density. In particular, the geodynamic processes of generation and development of a seismic destruction source zone in seismic-prone zones are considered to be associated with fracturing processes. Taking into account this, it is natural to use the space-time function of the density of cracks in a destruction source zone and in those of anomalous geophysical fields at the Earth's surface as a quantitative characteristic of the basic process generating anomalies-precursors. An integral function of the form $\theta(x, y, t) = \operatorname{div} \overrightarrow{U}$ (where $\overrightarrow{U}$ is a geophysical field recorded at the Earth's surface) was proposed by A.S. Alekseev. With the help of this function, one can approximately describe the density of cracks in a medium [1]. The function $\theta(x, y, t)$ can be called the function of a medium dilatancy. The creation of a method to determine

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the function $\theta(x, y, t)$, specifically, a method of vibroseismic monitoring of seismic-prone zones, is a challenging problem of active seismology.

2. Informative parameters of the seismic wave field in active monitoring

The detailed data on the medium zones structure with time-varying fracturing can be provided by the seismic method of observing P- and S-waves from powerful controllable vibroseismic sources. The efficiency of the vibroseismic monitoring method with this approach is justified both theoretically and methodologically in [2]. With the help of this method, the presence of cracks in destruction zones and a change in their volume density in the periods between monitoring sessions can be determined from the changes in the anisotropy coefficients and in wave propagation velocities.

The main idea of this paper is to increase the list of informative parameters of seismic wave fields taken as controlled ones in the problem of active monitoring of fluid-saturated and fractured media.

2.1. Parameters of wave field nonlinearity. The medium fracturing is a physical basis for the development of nonlinear propagation processes of seismic oscillations in destruction source zones. This is the reason for taking into account the parameters of wave field nonlinearity characterized by higher harmonics, which enrich the initial sounding vibroseismic oscillations. In this paper, the transformation of wave fields is analyzed by studying vibrational seismograms obtained by vibrational sounding of the regions adjacent to the mud volcano Shugo (the Taman mud volcano province). Seismic signals were recorded along longitudinal profiles at the traverses "vibrator—recording seismic station—mud volcano" and "vibrator—volcano—recording seismic station". In the latter case, the volcano was located between the vibrator and a seismic station [3]. Spectral-time functions (STFs) were calculated for vibrational seismograms obtained with both ways of recording [4]. Some forms of functions for the both investigated variants are presented in Figure 1. The sounding distance was $R = 3290$ m for the vibrator and the seismic station located at the profile in front of the Shugo volcano (Figure 1a) and $R = 3380$ m for the volcano located between the vibrator and the seismic station (Figure 1b).

A comparison of the two STFs obtained clearly shows the contribution of the volcanic construction to the broadband enrichment of the oscillation spectrum: a tenfold extension of the dominant oscillation spectrum is observed. Such effects can be related to the transformation of radiated signals on nonlinear structures of a geological medium with seismic waves propagating in fluid-saturated formations, such as effluent channels of mud volcanoes.

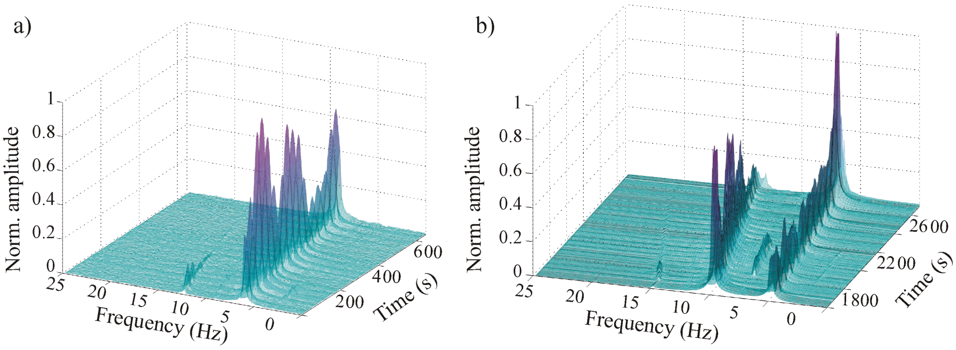

Figure 1. Spectral-time functions of vibrational correlograms

A numerical estimate of the influence of the fracturing process in a medium on nonlinear effects of oscillations propagation was obtained for the following model case. Chaotically distributed spheroidal voids, uniformly scattered in a homogeneous and isotropic medium are taken as the initial fracturing model. The nonlinearity coefficient is determined by the ratio between the amplitudes of the second and the first harmonics of the harmonic oscillations behind a fractured medium by the following expression:

$$\frac{u_2}{u_1} = \frac{1}{8}\frac{U_x B k_P^2 x}{M_0},$$

where $k_p = \omega/c_p$, B is the function depending on the medium fracturing and its elasticity parameters, M_0 is the number, also dependent on the elasticity characteristics of the continuum, x is the wave path length, and c_p is the velocity of P-waves.

The nonlinearity coefficient of the monochromatic wave shape versus the linear sizes of cracks determined by the ratio between the major and the minor axes of a spheroid, α, is shown in Figure 2. The plots were calculated for the following parameters: Young's modulus $E = 1.5 \cdot 10^{10}$, Poisson's coefficient $\nu = 0.42$, static pressure $p_0 = 10^3$ Pa, oscillation frequency $f = 7$ Hz, P-wave velocity $C_p = 5500$ m/s.

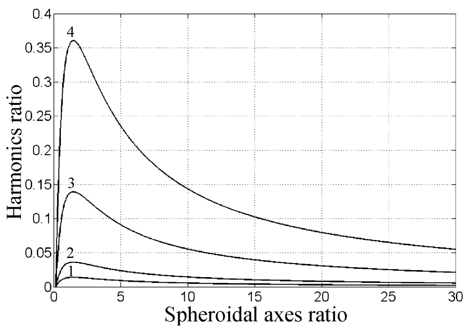

Figure 2. The nonlinearity coefficient of the monochromatic wave shape versus the ratio between the spheroidal axes simulating cracks in granite

These curves were obtained for wave path length $x = 10$ km (curves 1 and 2) and $x = 100$ km (curves 3 and 4); vibrational speed $U_x = 2.7 \cdot 10^{-8}$ m/s (curves 1 and 3) and $U_x = 70 \cdot 10^{-8}$ m/s (curves 2 and 4).

2.2. Fractals of scattered waves. The field of scattered waves randomly distributed in time and space contains much information about a medium heterogeneity. It is necessary to determine their especially high sensitivity to fine structural changes of a complicated medium in destruction source zones and thereby extract additional information about geodynamic processes. The appearance of scattered waves in vibrational seismograms after head waves is shown in Figure 3b. In contrast to the vibrational seismograms obtained for the vibrator and the seismic station located at the profile in front of the volcano (Figure 3a), one can easily see a more complicated structure of seismograms obtained for the seismic station located behind the volcano. This is evidently caused by the passage of vibroseismic oscillations through the volcano body.

Figure 4 presents the fractals of seismograms, which are projections of STFs (see Figure 1) on the "frequency–time" plane, to show the wave field structure in the frequency–time range. The amplitude values of STFs are shown in different colors. A 2D representation of parameters of seismic waves

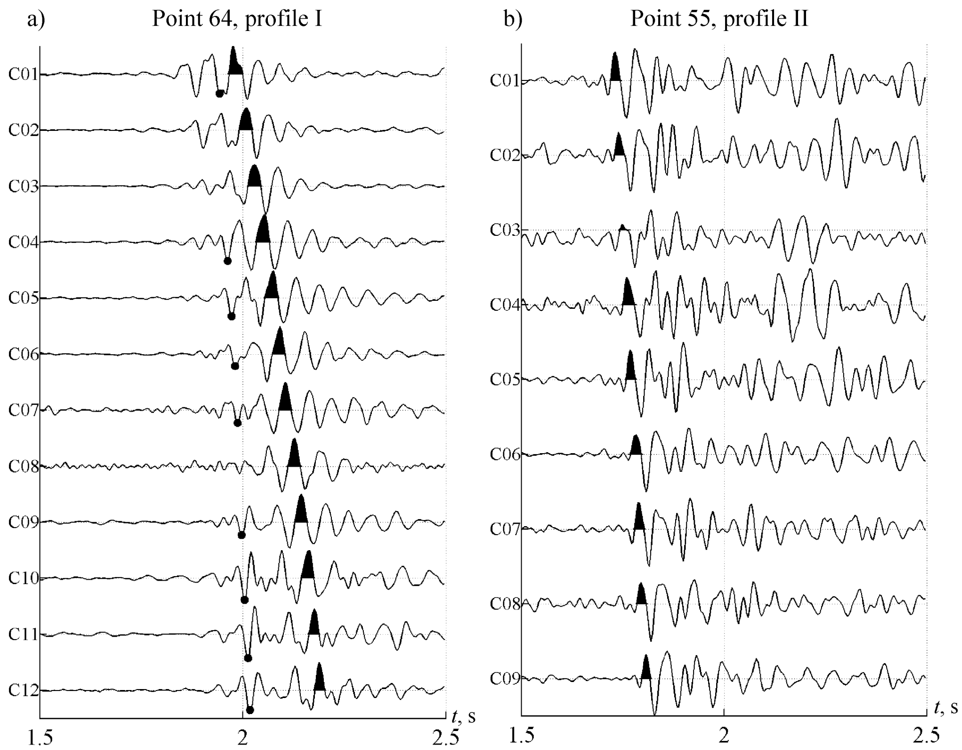

Figure 3. Vibrational seismograms obtained at the traverse "vibrator — Shugo volcano": a) $R = 3290$ m (the volcano is on one side of the vibrator and the seismic station); b) $R = 3380$ m (the volcano is between the vibrator and the seismic station)

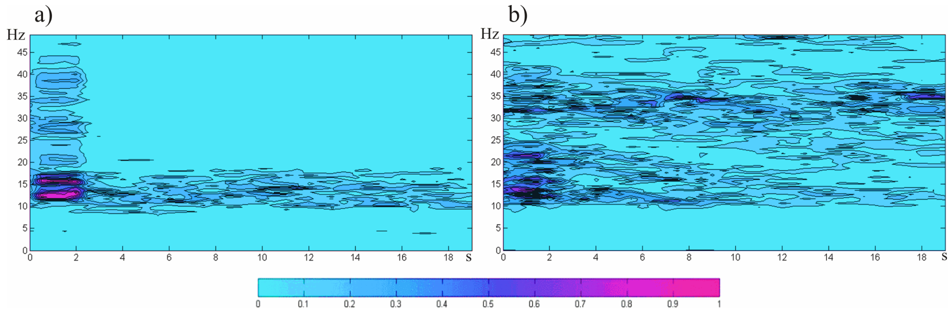

Figure 4. Fractals of vibrational seismograms obtained at the traverse "vibrator—seismic station—Shugo volcano": a) $R = 3290$ m (the volcano is on one side of the vibrator and of the seismic station); b) $R = 3380$ m (the volcano is between the vibrator and the seismic station)

in frequency and time shows, first of all, compactness of the distribution of the frequency–time parameters of dominant waves (head waves shown in the purple color) recorded at the profile in front of the volcano. On the contrary, the wave pattern recorded by the seismic station behind the volcano is characterized by "smearing" of these parameters on the "frequency–time" plane. Thus, the transient character of the field between these two states caused by the development of the processes of fracturing and fluid-saturation can be characterized by means of the fractals considered. They, together with other parameters, can be an efficient instrument for tracking these processes.

2.3. Variations of wave shapes in a tectonic fractures zone. The shape variations of the main seismic wave types are an additional informative feature characterizing the influence of destruction zones on passing seismic waves. This is the case, first of all, for S-waves. Earlier, N.N. Puzyrev detected that the influence of anisotropy on the passage of P- and S-waves is different. Therefore, it was soon realized that the anisotropy itself is a very "bright" characteristic of a medium that can be efficiently studied on the basis of multiwave seismics [6, 7]. Waveform variations were studied in experiments on vibrational sounding of tectonic fractures in the Novosibirsk region. The arrangement of sensors on both sides of a fracture is shown in Figure 5.

Figure 6 shows vibrational seismograms obtained by CV-40 vibrator for Z-component with seismic receivers located on both sides of the fracture at distances of 86.9 km and 92.9 km (the village of Starososedovo) and 36.1 km and 39.5 km (the village of Koinikha). When comparing the seismograms one can clearly see destruction of the waveforms of the main wave types caused by the fracture structures.

This disruption can be quantitatively estimated by measuring the correlation of waveforms recorded in front of the fracture and behind it. The table

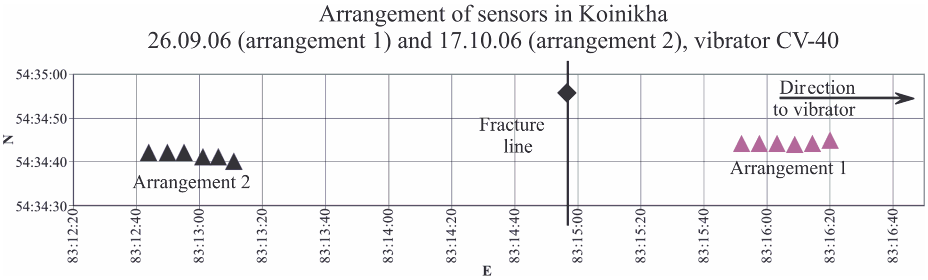

Figure 5. Arrangement of sensors on the fracture sides

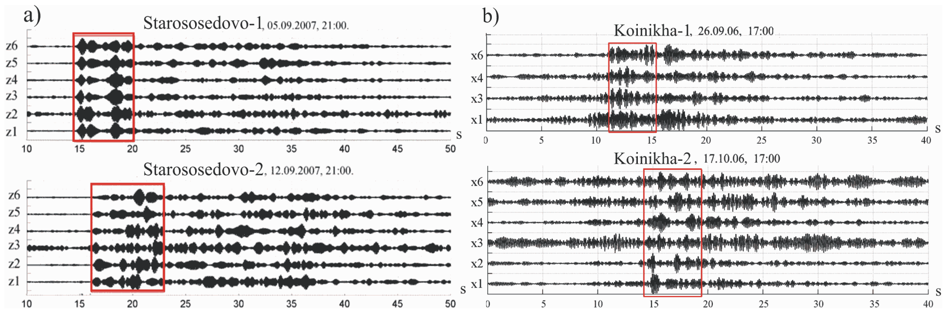

Figure 6. Vibrational seismograms recorded on both sides of the fracture in Starososedovo (a) and Koinikha (b)

presents estimates of the correlation coefficients of the vibrational seismograms along Z-component for the two fracture zones (Starososedovo-1 and Starososedovo-2; Koinikha-1 and Koinikha-2).

Correlation coefficients of the form $K(z_1, z_1)$, $K(z_1, z_2)$, ..., $K(z_1, z_6)$, that is, between the seismograms obtained with the first sensor and the seismograms obtained with other sensors in zones with P- and S-waves, were calculated.

One can see from this table that whereas in the column "Starososedovo-1" (in front of the fracture), the cross-correlation coefficient values

Cross-correlation coefficient of waveforms

Sensor components	Koinikha-1	Koinikha-2	Starososedovo-1	Starososedovo-2	Sensor components	Koinikha-1	Koinikha-2	Starososedovo-1	Starososedovo-2
x1	1.000	1.000	1.000	1.000	z1	1.000	1.000	1.000	1.000
x2		0.124		0.177	z2			0.620	0.433
x3	0.325	0.167	0.210	0.220	z3	0.513	0.293	0.798	0.509
x4	0.387	0.120	0.091	0.181	z4	0.376	0.333	0.836	0.560
x5		0.177	0.163	0.097	z5			0.840	0.357
x6	0.313	0.144	0.131	0.163	z6	0.424	0.206	0.789	0.377

are within 0.620–0.840, for "Starososedovo-2" (behind the fracture) the range of values of the corresponding estimates is 0.377–0.560. Similar estimates obtained along Z-component for the point "Koinikha" are 0.424–0.513 and 0.206–0.333, respectively. The corresponding estimates obtained along X-component for the point "Koinikha" are 0.313–0.387 and 0.124-0.177, respectively. Thus, there is an evident tendency for a decrease in the waveform correlation in seismograms introduced by the fracture.

3. Conclusion

The results presented are based on the multidisciplinary approach developed by Academician A.S. Alekseev to solve the problem of active seismic monitoring of the processes of fracturing and dilatancy developing in seismic- and volcano-prone zones. In addition to the approach consisting in tracking changes in the anisotropy coefficients of the medium and the propagation velocities of P- and S-waves, it is proposed to take into account the dynamic characteristics of the wave field, which make it possible to take into account the waveform variations and nonlinear transformation of wave fields associated with geodynamic processes developing in destruction source zones.

The approach in question is supported by experimental investigations resultson vibrational sounding of mud volcanoes in the Taman mud volcano province and the tectonic fracture in the Novosibirsk region. The efficiency of using these parameters of the wave field to solve the problem of active seismic monitoring is shown. In this case, the problem of estimating the dynamics of geodynamic processes in the destruction source zone becomes a multiparametric problem, which can be solved by pattern recognition methods.

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