ISSN 1028-334X, Doklady Earth Sciences, 2007, Vol. 413A, No. 3, pp. 397–401. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © B.M. Glinskii, A.L. Sobisevich, M.S. Khairetdinov, 2007, published in Doklady Akademii Nauk, 2007, Vol. 413, No. 3, pp. 398–402.

GEOPHYSICS

Experience of Vibroseismic Sounding of Complex Geological Structures (with the Shugo Mud Volcano as an Example)

B. M. Glinskii[a], A. L. Sobisevich[a], and M. S. Khairetdinov[b]

Presented by Academician A.S. Alekseev April 3, 2006

Received April 17, 2006

DOI: 10.1134/S1028334X07030178

The last 20 years of the 20th century were marked by the development and application of methods of active seismology based on the application of seismic vibrators [1, 2]. One of the main trends in this field is related, first of all, to the solution of the problem of forecasting natural disasters and earthquakes. The methods developed in this field are based on the study of the variations in the stress–strain state of the Earth's crust preceding an earthquake. Finally, this problem is related to the search for earthquake precursors [3]. The perspectives of application of the vibroseismic method for solving problems of such a class are conditioned by the possibilities of achieving precision accuracy in the measurements of spatiotemporal characteristics of the anomalies of seismicity fields during the preparation of earthquake sources [4, 5].

In the development of this method of active seismic monitoring in natural catastrophe zones, we have suggested to extend the vibroseismic method for monitoring active volcanoes. Some theoretical calculations of the expected results were carried out earlier [6–10].

In this work, we present preliminary results of vibration sounding of Shugo mud volcano (hereafter, Shugo Volcano) carried out for the first time in the practice of seismic research on volcanoes.

Experimental works were designed to accomplish the following tasks: (i) to study the peculiarities of wave processes in the volcanic edifice region and estimate their contribution to the parameters of the recorded seismic fields; (ii) to study the conditions of the transformation of wave fields and resonance phenomena in geological structures of the volcano; and (iii) to construct a velocity section of the geological medium in the Shugo Volcano region.

The crater of Shugo Volcano stands out among mud volcanoes of the Taman region and Northwestern Caucasus. It has the shape of a large cup with a volcanic edifice of light gray breccia at the center. The cup resembles a subsidence caldera. This is a distinguishing feature of Shugo Volcano relative to other volcanoes of Taman and Northwestern Caucasus. In this connection, the volcanic edifice is most interesting not only from the geological, but also from the seismological point of view. Therefore, we chose this object for approbating our technology of monitoring complex geological objects.

The research method used in the investigation was performing longitudinal profiles over vibrator–recording seismic station–volcano and vibrator–volcano–recording seismic station traverses. A seismic exploration vibrator of the SV-10/100 type was used. The seismic station included 12 groups of seismic sensors. The groups were located over a linear profile with a step of 30 m. Each group consisted of five sensors of the SB-5 type. The method of investigation consisted of sounding sessions at four spatially separated points denoted as points 55, 62, 63, and 64 with the distances between neighboring points equal to 550, 1175, and 2115 m, respectively. In addition to the displacement of the vibrator, the seismic groups were reorganized along the traverses mentioned above within the source–receiver base distance (500–5500 m). Soundings at the mentioned points corresponded to each spatial position of seismic groups. The number of repeated sessions of soundings at each point of the vibrator location varied within 5–7. Such a number was enough from the point of view of increasing noise stability of vibration seismograms under conditions of increased seismic noises in the volcano region. Vibration seismograms $\bar{r}(m)$,

---

[a] *Institute of Computational Mathematics and Mathematical Geophysics, Siberian Division, Russian Academy of Sciences, pr. akademika Lavrent'eva 6, Novosibirsk, 630090 Russia*

[b] *Joint Institute of Physics of the Earth, Russian Academy of Sciences, ul. Bol'shaya Gruzinskaya 10, Moscow, 123995 Russia; e-mail: alex@ifz.ru*

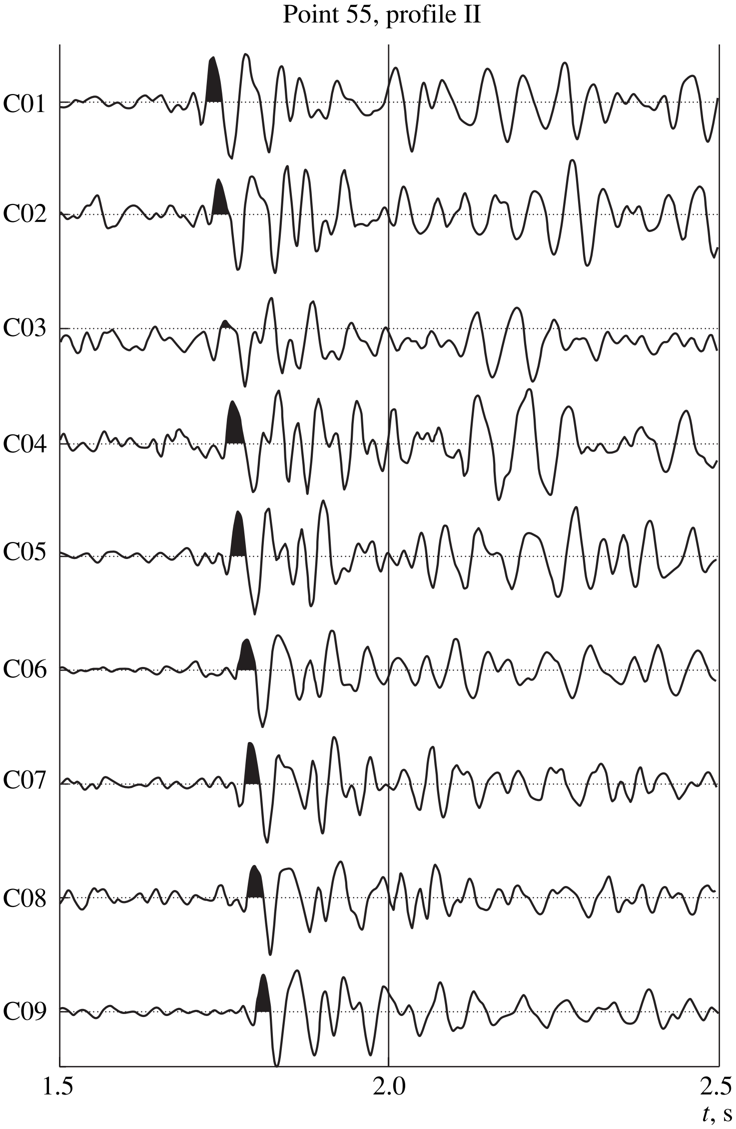

Fig. 1. Vibration seismograms across the vibrator–Shugo Volcano–seismic station traverse. The vibrator–seismic station distance is 3380 m. (C01–C09) Records of vertical components of the field.

which are similar to explosion seismograms, were calculated according to the following algorithm

$$\bar{r}(m) = \frac{1}{L}\sum_{i=1}^{L}\sum_{n=0}^{N-1} x_n^{(i)} S_{n-m}, \qquad (1)$$

$$m = 0, 1, \ldots, M-1, \quad i = 1, 2, \ldots, L,$$

where M is the number of discrete counts of the vibration seismogram; L is the number of averaging; N is the set of discrete counts of the recorded input signal $x_n = x(t_n)$; $S_n = S(t_n)$ is the reference signal with linear frequency modulation (LFM) of the following form

$$S(t) = a(t)\cos\left(2\pi f_0 + \frac{\beta t^2}{2}\right),$$

with the following parameters: $a(t)$ is the envelope curve, f_0 is the initial sweep frequency, β is the frequency sweep rate equal to $\beta = \frac{f_{\max} - f_0}{T}$, where $f_{\max}$ is the maximal frequency and T is the duration of sweep. The following values were accepted for the experiment: $f_0 = 10$ Hz, $f_{\max} = 64$ Hz, and $T = 60$ s.

Vibration seismograms obtained in the experiments are characterized by a high ratio of the level of signal waves to noise, which is as high as 20 in some specific cases. Figure 1 shows an example of vibration seismograms obtained as a result of sounding Shugo Volcano on the vibrator–volcano–seismic station traverse. In this case, the vibrator and seismic station were located at distances of 1500 and 1880 m, respectively, from the volcano.

Other important characteristics of vibroseismic signals are spectral temporal functions (STF), which allow us to characterize the spectral structure of the wave seismic field in time. The characteristic peculiarities of the spectra of recorded vibroseismic signals and calculated vibration seismograms were studied using three such functions. The STF related to both types of signals are written as

$$F_x(\omega_k, t_q) = F_x(k, q) = \sum_{n=0}^{N_1-1} x_{n+q}\exp\left(-j\frac{2\pi kn}{N_1}\right), \quad (2)$$

$$F_r(\omega_k, t_l) = F_r(k, l) = \sum_{m=0}^{M_1-1} r_{m+l}\exp\left(-j\frac{2\pi km}{M_1}\right), \quad (3)$$

where $n = 0, 1, \ldots, N_1 - 1$, $q = 0, 1, \ldots, N_2 - 1$, $N_1N_2 = N$, $N = \frac{T}{\Delta t}$, T is the total time of the analysis; Δt is the quantizing interval of the initial signals; $m = 0, 1, \ldots, M_1$, $l = 0, 1, \ldots, M_2$, and $M_1M_2 = M$.

Figure 2 shows an example of the graphs of functions (3) related to vibration seismograms. One of them (Fig. 2a) was obtained before the volcano, i.e., over the vibrator–seismic station–Shugo traverse, whereas the second graph (Fig. 2b) was obtained beyond the volcano, i.e., on the vibrator–Shugo–seismic station traverse.

The accepted technology of the field experiment made it possible to fulfill the following tasks: (i) to study the peculiarities of wave processes in the vicinity of the volcanic edifice and to estimate their contribution to the parameters of recorded seismic fields; (ii) to construct a velocity section of the geological medium in the Shugo Volcano region.

Let us note the most interesting characteristic peculiarities of recorded seismic fields obtained by means of vibroseismic sounding of Shugo Volcano.

1. The wave field structure is significantly complicated by propagation of seismic oscillations through a complex geological medium of the volcanic edifice as compared to the pattern of wave processes recorded on seismograms before the volcano. In the temporal domain, this leads to the appearance of chaotically distributed secondary waves following the leading wave on vibration seismograms (Fig. 1), which are absent in the wave field structure before the volcano, i.e., when the source and receiver are located on one side of the volcano. Therefore, an increase in the duration of seismograms with the dominating part of amplitudes up to 1.5–2.0 s is observed in the first case compared to 0.3 s in the second case at practically equal vibrator–seismic station distances corresponding to both cases of sounding.

2. The effect described above is accompanied by multiple widening of the spectra of the response of the media. This was proved by the comparison of two sets of spectral temporal functions of types (2) and (3) obtained before and beyond the volcano at comparable source–receiver distances. In particular, this follows from the comparison of the STF of vibration seismograms shown in Figs. 2a and 2b. A comparative analysis of both spectra of responses proves with confidence the contribution of fluid-magmatic structures of the volcanic edifice to the enrichment of spectra with oscillations that passed through the structures. Almost a 5-fold widening of the spectra of oscillations is observed in this case. Such effects can possibly be related to the transformation of spectra of the signals in nonlinear structures of the geological medium during the propagation of seismic waves in fluid-saturated formations, such as conduits of mud volcanoes.

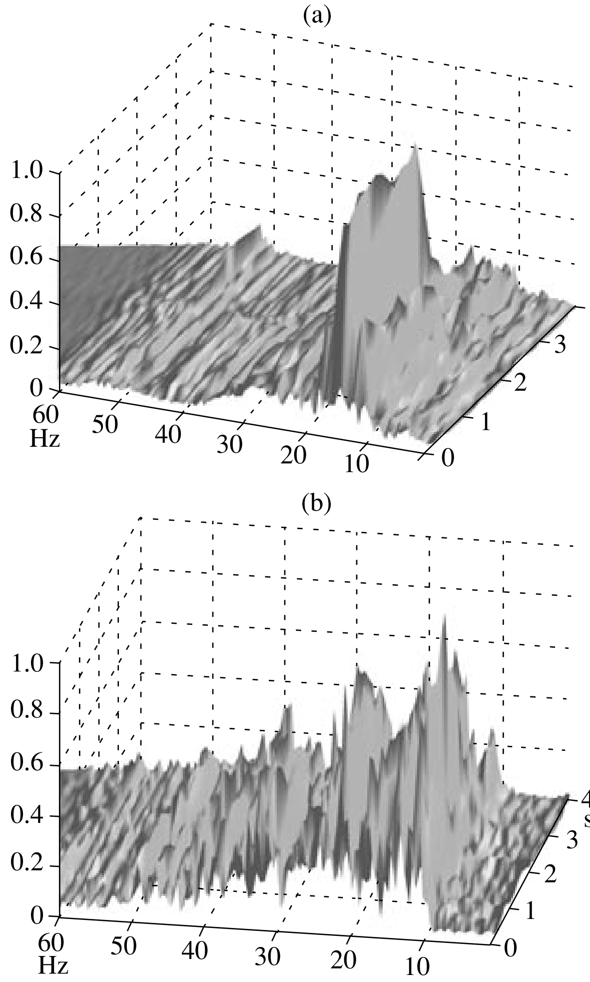

Fig. 2. Spectral temporal functions of vibration seismograms for vibrator–receiver distances: (a) $R = 3500$ m (up to Shugo); (b) $R = 3600$ m (beyond Shugo).

3. The forms of STF presented in Fig. 2 characterize additional peculiarities of the spectral composition of the wave field. For example, the response of the medium (before the volcano) to sounding with a wide band (10–64 Hz) sweep-signal is represented by a narrow band signal. The STF maxima, which characterize

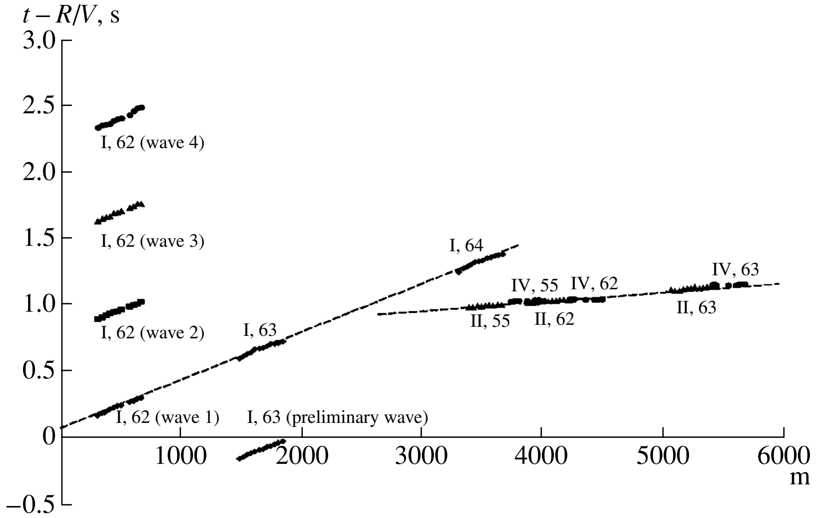

Fig. 3. Reduced hodographs of waves for profiles I, II, and IV and sounding points 55, 62, 63, and 64.

the resonance properties of the emitter–medium sequence of wave propagation, depend on distance R. They were recorded within 40–50 Hz at $R = 550$ m, within 20–30 Hz at $R = 1700$ m, and within 15–20 Hz at $R = 3500$ m. Thus, as the source–seismic station distance increases, the resonance shifts to the lower frequency domain. In the case corresponding to a distance of $R = 3500$ m, the form of the STF is shown in Fig. 2a.

4. At small distances from the source ($R = 550$ m), multiple harmonics (second, third, and fourth) appear in the seismic wave field. As the distance increases, the harmonics become weaker due to attenuation and they are not manifested after 1700 m.

5. The dominating noise level is observed on the STF of initial signals in the low-frequency range (lower than 10 Hz). A comparison of the STF of the initial vibroseismic signals and vibration seismograms obtained from Eqs. (2) and (3) demonstrates high selectivity of the correlation convergence (1), which makes it possible to effectively distinguish the sweep signal over the noise background. This explains the absence of noise in the low-frequency range (lower than 10 Hz) on the STF graphs shown in Fig. 2a.

6. Reduced hodographs of leading seismic waves (reduction speed $V = 4550$ m/s) obtained from the vibration sounding data demonstrate prominent linear time–distance dependences in the range 300–5000 m (Fig. 3). A hodograph obtained over the vibrator–receiver–volcano profile corresponds to an apparent velocity of 1740 m/s, which is repeated over different intervals of sounding accurate to 0.5%. The second hodograph that covers the profiles beyond the volcano and corresponds to the vibrator–volcano–seismic station location scheme (i.e., the volcano is located between the source and receiver) is associated with an apparent velocity of 3400 m/s accurate to 3%. Both hodographs were obtained from vibration seismograms with distinct entries of the leading waves. The leading waves corresponding to the second hodograph are shown in Fig. 1 as an example. These data obtained in the location of Shugo Volcano and vibration sounding range of 500–5000 m allow us to construct a model of a three-layer horizontally layered medium. The interface boundaries in this media are located at depths of 70 and 702 m.

7. Geodynamic effects related to the response of mud volcanoes and other fluid-saturated structures in the volcanic edifice to vibration were found during active monitoring of the volcanic edifice and the surrounding geological medium. Mud manifestations in the center of the volcano and at its periphery during long-term active seismic impact demonstrate a spatial anisotropy.

We recorded temporal redistribution of mud manifestations at all griffons of Shugo Volcano during the investigations. Some lateral griffons began flowing. The study of this phenomenon requires special additional experiments on mud volcanoes. This is even more important since such processes can indicate the preparation of regional-scale seismic events [7].

There are grounds to assume that the anomalous geophysical phenomena discussed above can mainly be related to the dynamic reconstructions of resonance-type dilatancy structures, which are developed in the mud volcanic edifice at all stages of its functioning [11].

Thus, methods of vibroseismic monitoring of complex geological formations are being developed in Russia. Within the framework of their implementation, this work demonstrates for the first time an active sounding of the volcanic edifice with Shugo Volcano (Taman mud volcanic province) as an example. During the field experiments, we compiled a seismic section in the volcanic region and studied conditions of the interaction of the vibroseismic fields with the volcanic edifice and the surrounding geological medium. The observed structural changes of the dynamic characteristics of wave fields provide new insights into the generation conditions of wave processes in the mud volcanic edifice. These experiments can serve as a basis for developing a system and method of monitoring active volcanoes using vibration sources.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research, project nos. 03-05-65292a and 05-05-64154a.

REFERENCES

1. A. S. Alekseev, B. M. Glinskii, A. L. Sobisevich, et al., *Active Seismology with Powerful Sources of Vibration* (IVMiMG SO RAN, Novosibirsk, 2004) [in Russian].
2. A. S. Alekseev, B. M. Glinskii, and V. V. Kovalevskii, *Active Seismology: Concept, Tools, and Problems. Global Changes of Nature, Environment, and Climate. Selected Publications* (Min-vo Nauki Tekhnol. RF, Moscow, 1997), pp. 165–188 [in Russian].
3. A. S. Alekseev, A. S. Belonosov, and V. E. Petrenko, in *Mathematical Modeling in Geophysics* (Novosibirsk, 1998), pp. 3–50 [in Russian].
4. B. M. Glinskii, V. V. Kovalevskii, and M. S. Khairetdinov, Geol. Geofiz. **40**, 422 (1999).
5. B. M. Glinskii, V. V. Kovalevskii, and M. S. Khairetdinov, Volcanol. Seismol. **21**, 723 (2000).
6. V. A. Babeshko, O. M. Babeshko, and A. L. Sobisevich, Dokl. Akad. Nauk **336**, 760 (1994).
7. L. E. Sobisevich and A. L. Sobisevich, *Wave Processes and Resonances in Geophysics* (OIFZ RAN, Moscow, 2001) [in Russian].
8. K. I. Loginov and A. L. Sobisevich, in *Development of Methods and Devices in Experimental Geophysics* (OIFZ RAN, Moscow, 1996), Vol. 2, pp. 174–180 [in Russian].
9. Yu. N. Makov, O. V. Rudenko, L. E. Sobisevich and A. L. Sobisevich, in *Development of Methods and Devices in Experimental Geophysics* (OIFZ RAN, Moscow, 1996), Vol. 2, pp. 194–200 [in Russian].
10. L. E. Sobisevich, V. I. Shumeiko, M. G. Seleznev, et al., *Local Resonances in Layered Media* (OIFZ RAN, Moscow, 2000) [in Russian].
11. V. V. Nikolaevskii, *Mechanics of Porous and Fractured Media* (Nedra, Moscow, 1984) [in Russian].