CHAPTER

Active vibromonitoring: experimental systems and fieldwork results 1.3

Valery V. Kovalevsky[1], Boris M. Glinsky[1], Marat S. Khairetdinov[1], Alexey G. Fatyanov[1], Dmitriy A. Karavaev[1], Lyudmila P. Braginskaya[1], Andrey P. Grigoryuk[1] and Tsyren A. Tubanov[2]

[1]*Institute of Computational Mathematics and Mathematical Geophysics SB RAS, Novosibirsk, Russia*

[2]*Geological Institute SB RAS, Ulan-Ude, Russia*

Chapter Outline

1.3.1 Introduction

Over the past 30 years, in an effort to improve seismic hazard prediction, seismologists have turned to active geophysical monitoring methods, using powerful seismic vibrators to investigate changes in the geologic medium's stressed-deformed state within seismically active zones. This scientific direction has been vigorously pursued at institutes within the Siberian Branch of the Russian Academy of Sciences (SB RAS). During this period, several experimental systems for active monitoring have been created. They include powerful vibrational sources (with a vibrational force of 100 tons in the frequency range from 5 to 15 Hz), computer control systems, specialized mobile complexes VIRS-M, VIRS-K, and ROSA for precisely recording vibrational seismic signals, and data-processing systems. Recently, a method for active monitoring using wideband sweep signals and

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narrowband monofrequency signals radiated by seismic vibrators has been developed (Alekseev et al., 1997, 2004, 2005; Kovalevsky, 2006; Kovalevsky et al., 2016, 2017; Seleznev et al., 2004).

Active seismology investigations include experimental works using powerful vibrational sources of seismic waves, recording of vibroseismic signals, processing of vibroseismic data, mathematical modeling of wave fields for realistic velocity models of the Earth's crust, and analysis and comparison of experimental data with theoretical results. The tasks of large-scale vibroseismic investigations include studying the characteristics of vibroseismic fields, determining the structure of the Earth's crust, and verifying the existing velocity models, identifying informative features of geodynamic processes in vibroseismic monitoring of the geological medium.

1.3.2 Vibromonitoring experimental systems

A powerful low-frequency vibrator (namely, the CV-100) is the basis of this active monitoring system. This 100-ton vibrator consists of a ground platform, a heavy frame with a loading mass of about 120 tons, eccentric force units, and two electric motors. This vibrator (Alekseev et al., 2005) can radiate sweeps using time-varying frequency and monofrequency signals. Its computer control system provides an angular accuracy of 1–2 degrees. The duration of continuous operation ranges from 5 minutes to 1 hour; usually a 20–40-minute radiation session is sufficient to record sweep signals over a distance of 300–400 km and to obtain an impulse seismogram after correlation. Detection of the monofrequency signals can be done as far as 1400 km from the source.

At present, powerful low-frequency vibrators with eccentric excitation systems are installed at the test sites Bystrovka (near Novosibirsk), Babushkin (in the Lake Baikal region), and Goryachiy Kluch (near Krasnodar) (Alekseev et al., 2004, 2005). Fig. 1.3.1 shows the CV-100 vibrators at the Bystrovka and Baikal test sites.

Another type of powerful low-frequency vibrator is based on a mechanical system with variable resonance frequency. One of these, the hydro-resonance vibrator HRV-50, uses the resonant oscillation of a 60-ton water column located between two air springs in the vertical case (Fig. 1.3.2). Oscillations are excited by compressed air pushed into the air springs through special valves using a computer-controlled system. The HRV-50 produces a 50-ton vibrational force in the 2–10 Hz frequency range. It is a full-scale model of the 1000-ton superpowerful shaft vibrator, intended for monitoring at teleseismic distances (Kovalevsky, 1981, 2000).

Vibroseismic signals are recorded by stationary regional seismic stations located in the monitoring zone, as well as by mobile recording systems. Small seismic arrays with seismic sensors and autonomous digital recorders are the basis of the mobile recording systems. The frequency range of the recording systems is

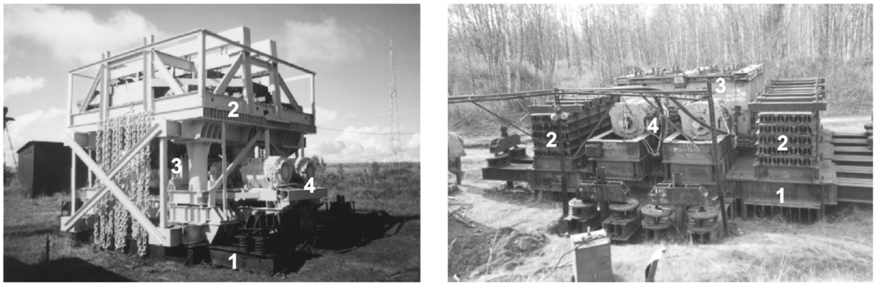

FIGURE 1.3.1

A view of CV-100 vibrators at the Bystrovka test site of SB RAS (left) and Baikal test site of SB RAS (right): (1) ground platform; (2) heavy frame with loading mass; (3) eccentric force units; and (4) electric motors. The vibrational force on the ground is 100 tons within the frequency range of 5–15 Hz. *SB RAS*, Siberian Branch of the Russian Academy of Sciences.

FIGURE 1.3.2

A view of the HRV-50 hydro-resonance vibrator at the Bystrovka test site of SB RAS. The vibrator's case is a vertically installed railway tank. The 60-ton water column and two air springs near the top and bottom are inside the tank. Oscillations are excited by compressed air passing through special valves: (1) ground platform, (2) tank, (3) air valves. The vibrational force on the ground is 50 tons within the frequency range of 2–10 Hz. *SB RAS*, Siberian Branch of the Russian Academy of Sciences.

1–100 Hz, the digit capacity of the digital recorders is 24 bit, and the sensitivity is 20 nV/bit or 0.15 nm/s/bit. It should be noted that the amplitude of vibroseismic signals can be 100 times less than the microseismic noise level when recorded at distances of more than 100 km from the vibrator.

Active vibrational monitoring using a CV-100 seismic vibrator is carried out in the seismic zone in the southern part of the Baikal region. The vibrator is located at a distance of 1 km from the Lake Baikal shore near the Babushkin city. During monitoring, the vibrator generates sweep signals and monofrequency signals at given time intervals. The generation and recording of vibroseismic signals are carried out at night, when the microseismic noise level is minimal. The vibrator generates several identical sweep signals and several monofrequency signals per night. These sessions have been performed once every month since 2003. The frequency range of the sweep signals is 6.25–10.059 Hz with a duration of 3272 seconds. The frequencies of monofrequency signals are 6.5, 7.0, 7.5, 8.0, 8.5, and 9.0 Hz. To record vibroseismic signals, seismic stations of the regional seismological network of the Buryat and Baikal Branches of the Geophysical Survey SB RAS and mobile seismic recording systems of the Institute of Computational Mathematics and Mathematical Geophysics SB RAS (ICM&MG SB RAS) and Geological Institute SB RAS (GIN SB RAS) are used. The monitoring area is 550 × 250 km in the southern part of the Baikal region (Tat'kov et al., 2013).

The method of vibroseismic monitoring using sweep signals is based on obtaining vibrational seismograms at recording points and analysis of time changes in the arrival times and amplitudes of individual wave groups. When monofrequency signals are used, monitoring is based on the principles of vibroseismic interferometry. When the vibrator radiates harmonic signals, a stationary wave field with a constant amplitude and phase is formed at each point of the geological medium. Changes within the medium in the stress-concentration zone (i.e., a developing earthquake zone) lead to changes in the characteristics of the stationary wave field on the surface where seismic signals are recorded. Active vibromonitoring using the vibrator's stationary wave fields in a seismically active zone of Baikal was performed for the first time in 2003. A scheme of the vibroseismic monitoring system in the Lake Baikal region is given in Fig. 1.3.3.

1.3.3 Active vibromonitoring experiments

1.3.3.1 Variations of seismic waves caused by the Earth's tides

In 1996–97 the ICM&MG of the SB RAS conducted experiments using low-frequency vibrating sources and the recording of signals at distances of 300–400 km. The goal of these experiments was to determine the active vibroseismic monitoring system's sensitivity through the detection of small variations in a seismic-wave-field caused by the Earth's tidal deformation processes.

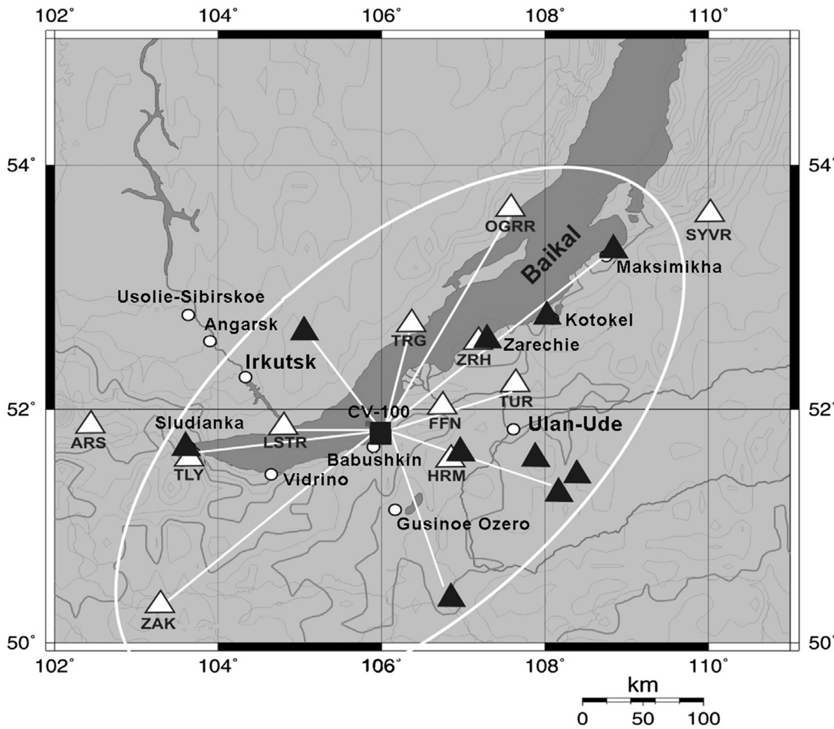

FIGURE 1.3.3

The scheme of the vibroseismic monitoring system in the Lake Baikal region: CV-100 vibrator (black square), mobile recording complexes (black triangles), seismic stations of the regional seismological network (white triangles). The 4–6 sweep- and monofrequency sessions have been carried out by the CV-100 vibrator overnight, every month since 2003. The monitoring area marked with a white ellipse is about 550 km × 200 km. The directions from the vibrator to recording complexes and seismic stations are marked with white lines.

Semidiurnal and daily tides (with periods of approximately 12 and 24 hours) exist on the Earth, and the deformational influence of such tides on the Earth's crust has some important ramifications for seismic monitoring. It is a global phenomenon that can be observed at any point on the Earth, exhibiting periodic changes that may be predicted with a very high degree of accuracy, and can serve as a natural standard for deformation forces in the lithosphere.

Considerable experimental effort has been devoted to investigations of how the tidal deformations of the Earth's crust influence changes in seismic wave velocities. The main question for this research has been: Do tidal deformations on the order 10^{-7}–10^{-8} result in much larger relative variations in seismic wave velocities? The main difficulty with experiments associated with this question has been the limited accuracy of measurements. When the arrival-time variations in the P and S waves of earthquakes were used for analysis, the greatest variations in seismic waves velocities (10^{-2}) correlated with the phases of Earth's tides have been detected (Popandopulo, 1982). In investigations using explosions and earthquakes, variations in velocities have been comparable to a measurement accuracy of 10^{-3}–10^{-4} (Eisler, 1967; Gamburtsev, 1992). Experiments conducted using vibrators had the same accuracy and were carried out at an offset of 10 km (Aki et al., 1970; De Fazio et al., 1973). In Scandinavia, there has been an experiment involving the recording of the monofrequency radiation of a hydropower station (by the group NORSAR) at distances of 5–14 km (Bungum et al., 1977). In this experiment, relative changes in seismic wave velocities of 10^{-3} were detected. Another experiment, carried out by the Siberian Branch of RAS, used a low-frequency vibrator with an offset of 125 km to collect vibrograms that detected variations in first-arrival times (Yushin et al., 1994). These did not show velocity variations greater than 10^{-4}.

In all these experiments, if variations in seismic velocities were observed, they had values comparable to the accuracy of the measurements. A reliable conclusion with respect to the connection between seismic velocity variations and crustal tidal deformations was not possible. However, *some* correspondence was found: if the source characteristics were not precisely known, larger variations in seismic wave velocities connected with tidal processes could be obtained in experiments. The results of these experiments have shown that for detecting variations in seismic waves caused by the Earth's tides, large offsets (several hundreds of kilometers) and highly stable sources are necessary for increasing the accuracy of measurements.

1.3.3.2 Vibroseismic interferometry experiments

Vibroseismic interferometry was used in experiments conducted at ICM&MG SB RAS. This method is based on excitation and recording of monofrequency signals from powerful vibrators. Because of the high stability of the monofrequency signals radiated by the vibrators, their parameters are determined with high accuracy at the recording point. For the amplitude spectrum of such signals, the signal/noise ratio reaches values of 50–100 over distances of 300–400 km, for sounding sessions with durations of 20 minutes. Thus the amplitudes of monofrequency signals are determined with an accuracy of 1%–2%. Correspondingly, the accuracy of angular-phase measurements is 0.5–1 degree, which enables detection of travel-time changes within several milliseconds. Such high sensitivity allows detection of small propagation-velocity variations (Glinsky et al., 1999, 2000; Kovalevsky, 2004, 2006).

At the Bystrovka test site in 1996–97, excitation of monofrequency signals in a frequency range of 6–8 Hz (with intervals of 1 and 3 hours) was carried out using the 100-ton vibrator CV-100 over a 3–4-day period. Signal recordings were made at distances of 430 km (seismic station Ust-Kan, Republic Gorny Altai, 1996) and 356 km (Savushky, Altai, 1997). In these experiments, investigators used GPS time synchronization, both at the vibrator and at the remote receiver points. At the Bystrovka test site of SB RAS, the recording system included a three-component seismometer installed 30 m from the vibrator. The scheme of the experiment (at a distance of 356 km) is presented in Fig. 1.3.4.

In the first experiments (in 1996), the recording of vibroseismic signals was made by the six-channel system CROSS-PC, with three three-component seismometers (SK-1P) installed on bedrock near the Ust-Kan seismic station, Republic of Gorny Altai. GPS was used for time synchronization of the source and the recording systems. Monofrequency signals of 6.75 Hz were used, because they had a maximal signal/noise ratio at the recording point. Periodically repeating radiation sessions were carried out to detect the daily variations in the parameters of the vibrosignals. Three series of periodic nocturnal soundings were done (on September 28−30, October 5−7, and October 14−16), in the phase of two syzygial tides and one neap tide. In each session, the duration of the sessions was 25 minutes (1500 seconds). Nine sessions were conducted each night. They followed one another with a gap of 1 hour, from 10:30 p.m. until 6:30 a.m. local time. (The choice of this schedule was determined by the low level of microseismic noise at night.)

Thus 27 measurements of monofrequency signals were taken at a distance of 430 km from the vibrator, in three series of soundings over 3 days duration each. These measurements were carried out irregularly in time during this 3-day series: nine measurements were conducted every night, while none were conducted during the day. As a result, investigators obtained nine time series with variations in monofrequency signals (for all three *X*, *Y*, and *Z* components) over an irregular time scale.

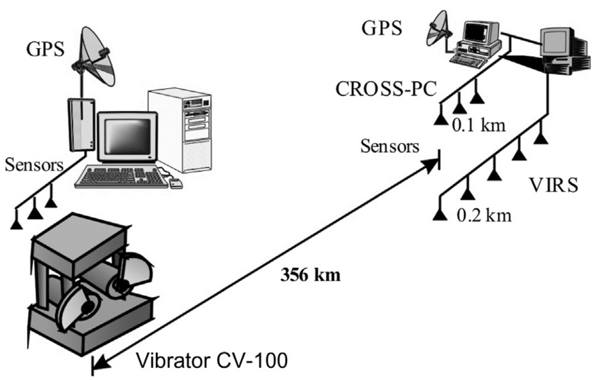

FIGURE 1.3.4

The scheme of the 1997 vibromonitoring experiment. The CROSS-PC and VIRS recording systems were located 356 km from the CV-100 vibrator. They have 3 and 5 three-component seismic sensors installed on the profile, with steps of 0.1 and 0.2 km, respectively. A control recording system was placed near the vibrator. GPS was used for time synchronization. Monofrequency-radiation sessions were repeated every 3 hours over 4 days.

In the experiments of 1997, two recording systems were used at a distance of 356 km from the vibrator, near the village of Savushky, Altai region. The VIRS recording complex had a 15-channel seismic array that included five three-component seismic sensors (SK-1P); the CROSS-PC system had three three-component seismic sensors. Monofrequency signals of two frequencies (6.3 and 7.0 Hz) were radiated for durations of 25 minutes each every 3 hours. The experiment lasted 4 days without interruption, resulting in a regular time series with 32 measurements for all sensor components. GPS was used for time synchronization.

1.3.3.3 Data processing and results

Processing of the recorded data was based on spectral analysis of the vibrational signal in the presence of the noise background. The 1200 seconds part of the record, 300 seconds after the beginning, was used for this analysis, which allowed us to use a stable-in-time monofrequency signal for the processing and to exclude the period of wave-field buildup connected with the arrivals of various waves. The amplitude and phase of the spectral components in a 0.0008 Hz interval around the excitation frequency were measured as parameters of the signal. For the session duration of 1000−1500 seconds, the amplitude of the spectral line of the signal is 20−40 times larger than the average spectrum level of noise.

Fig. 1.3.5 shows the spectra of driving monofrequency signals with frequencies of 6.3 and 7.0 Hz. The signal recorded at the Bystrovka test site of SB RAS had an amplitude that exceeded the noise level by a factor of 1000. Therefore the parameters of the radiated signal were determined with an error of 0.1% for the amplitude and 0.1 degree for the phase.

We evaluated the accuracy of our estimates from the power spectral density (PSD) of noise within a narrowband of frequencies near the spectral line of the

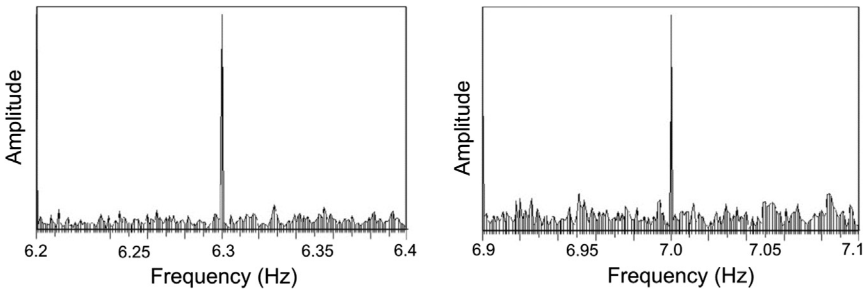

FIGURE 1.3.5

Spectra of monofrequency signals at frequencies of 6.3 and 7.0 Hz. The distance from Vibrator CV-100 is 356 km (Savushky, Altai). A radiation signal with a duration of 1200 seconds provides a signal-to-noise ratio of 20−40, and an accuracy in determining signal amplitudes and phases of 2%−4% and 1−2.5 degrees, respectively, at the recording point.

recorded signal. To evaluate PSD, we used a frequency interval of 0.1 Hz, near the driving monofrequency, which included 100–150 spectral lines and gave a representative sample for estimating the statistical characteristics of noise. The PSD of noise was estimated separately for each session—it improved the reliability of estimates for the nonstationary seismic noise.

We determined that the usual error in estimating the signal amplitude (for the noise level at the recording points in these experiments) was about 2%–5% for the signal component with maximal amplitude, and the error of the phase was 1.5–2.5 degrees.

From these experiments, we obtained the time series of amplitudes and phases for each component of the three-component seismometers. The components with the maximal signal/noise ratio were chosen for further analysis. Thus for a frequency of 7.0 Hz, the components *X*4, *Y*3, *Y*4, *Y*5, and *Z*3 were chosen; and for a frequency of 6.3 Hz, the components *X*3, *X*4, *Y*4, *Y*5, *Z*4, and *Z*5 were chosen.

Preparing the time series of vibrosignal phases for further analysis was conducted in several stages. Time synchronizations of the recording system (by GPS) were made several times during the experiment. Consequently, it was necessary to account for the precise starting times of the record files in determining the phases of signals. Similar time series were constructed for the amplitudes of signals. (The preparation of the amplitude series was somewhat easier than the preparation of the phase series, since the former was not connected with the precise recording times.) In detecting the amplitudes of spectral lines for various components, the amplification factors related to the recording complex and vibrator force were taken into account. The time series of phases and amplitudes at components *X*, *Y*, *Z* for frequencies of 6.3 and 7.0 Hz are shown in Figs. 1.3.6 and 1.3.7, respectively.

To find latent periodicities, we analyzed the time series of signal amplitudes and phases to determine the relationship between variations in signal amplitudes and phases, and Earth tides. A Fourier transform for the time series—with a nonuniform distribution based on approximation by periodic functions using the least squares method—was used to process the results of the experiments at a distance of 430 km. The amplitude of the spectrum component was determined from functional minimization.

Spectral components for all-time series of the amplitudes and phases were determined within a 6–30-hour interval, after which the spectrum of each time series was normalized to maximum. The normalized spectra were averaged, from which the spectrum of the time parameters averaged over all-time series of the vibrosignals was obtained:

$$S(T) = \frac{1}{M}\sum_{i=1}^{M}\frac{S_{\varphi i}(T)}{\max_T}\left(S_{\varphi i}(T)\right), \tag{1.3.1}$$

where $S(T)$ is the spectrum of variations in parameters averaged on the time series of the vibrosignals, i is the number of time series, M is the total number of phase and amplitude time series, T is the period, and $S_{\varphi i}$ (T) is the amplitude in the spectrum of time variations.

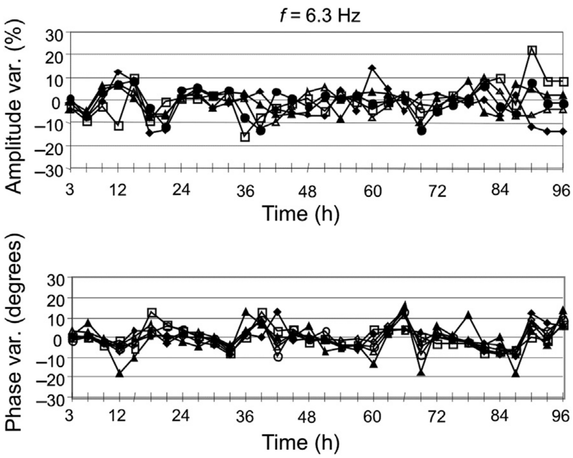

FIGURE 1.3.6

Time series of the amplitude and phase variations for a frequency of 6.3 Hz. They include 32 points, each corresponding to one of 32 sessions carried out every 3 hours over 4 days. Distance from the CV-100 vibrator is 356 km. Five components with the maximal signal/noise ratio were chosen. Visible periodicities become apparent after spectral analysis.

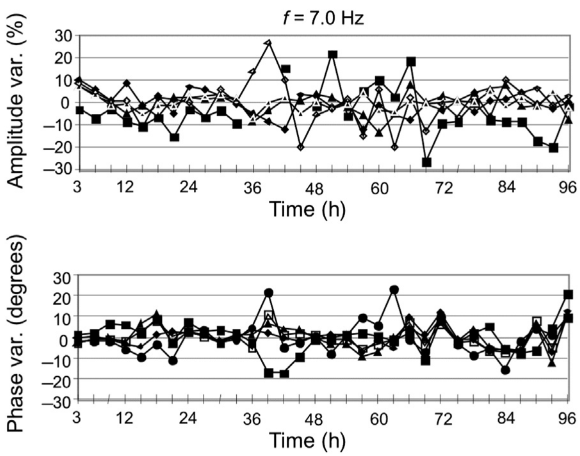

FIGURE 1.3.7

Same as in Fig. 1.3.5, but for a frequency of 7.0 Hz.

The average spectrum of the parameter variations is presented in Fig. 1.3.8. There are maxima of the spectrum with periods of 12 and 24 hours; the values of the signal amplitude variations are 2%–4%, and the appropriate value of the phase variations is 1–2 degrees. Note that the accuracy of these estimates is

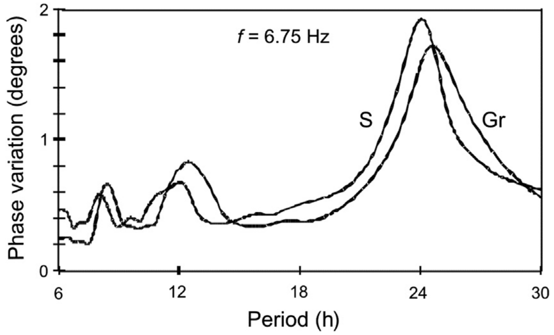

FIGURE 1.3.8

The average spectra of variations in the phase of monofrequency vibrosignals (S) and tidal variations of gravity (Gr). The signal frequency is 6.75 Hz. The distance from the CV-100 vibrator is 430 km. Spectra have correlated maxima with periods of 12 and 24 hours for seismic and gravity data. The subordinate spectrum maximum is caused by the nonuniform time scale of the data.

higher than the accuracy of an individual estimate in measuring amplitude and phase within one session. For the estimation of one value, we use the information from an ensemble of nine time series of variations, with 27 points in each series. Therefore it can be assumed that the dispersion of the amplitude estimate decreases approximately 5–10 times. It may reduce the error in determining amplitudes by 0.5%–1% and in determining phases by 0.2–0.5 degrees. Fig. 1.3.8 shows also the spectrum of tidal acceleration, obtained from gravitational measurements. There are maxima with periods of 12 and 24 hours, corresponding to the semidiurnal and daily periods in the spectrum of tidal acceleration.

Despite the fact that time series with irregular points give subordinate maxima in the spectrum, as is clear from Fig. 1.3.8, the 1996 experiments performed at a distance of 430 km showed for the first time the presence of daily and semidiurnal periodicity in the time variations within vibrosignal parameters, and have enabled us to assume their connection with tidal deformation processes in the Earth's crust.

Experimental techniques were considerably improved in 1997 in experiments at a distance of 356 km from a vibrator (near the village of Savushky, Altai region). In those experiments, we conducted a uniform series of radiation and recording sessions with a periodicity of 3 hours over 4 days. CROSS-PC and VIRS recording systems were used, with three and five three-component seismic sensors installed on the profiles, with steps of 0.1 and 0.2 km, respectively. This uniform series of radiation and recording sessions allowed us to construct the correct spectrum on a regular time scale without subordinate maxima, and to choose a time series of amplitudes and phases from channels with the highest signal/noise ratios.

In determining the spectrum of time variations, we took into account that the accuracy of measurements for various values in the time series was not equal. Such accuracy is related to the signal/noise ratio in each session, and usually decreases in the afternoon, owing to the increase in human-caused microseismic noise. Therefore in searching for latent periodicity, we used Fourier transforms for uniform time series with unequal accuracy points, also based on approximation by periodic functions with the least squares method. The amplitude of a spectrum component with period T was determined from the following minimization functional:

$$W_i = \sum_{n=1}^{N} \left(\frac{A_{in}}{\sigma_{in}}\right)^2 \left(\varphi i(n\tau) - S_{\varphi i}(T) \sin\left(\frac{2\pi n\tau}{T} + \alpha_i\right)\right)^2, \tag{1.3.2}$$

where W_i is the functional for the time series i of variations for the phase φ_i, N is the number of sessions, τ is the time step between consecutive sessions, T is the period, $S\varphi_i$ (T) is the amplitude over a spectrum of time variations in the phase for the period T, α_i is the phase of the spectral component, A_{in} is the amplitude of the monofrequency signal in this channel in the nth session, and σ_{in} is the dispersion of microseismic noise in this channel in the nth session.

The spectral components for all-time series of amplitudes and phases were determined over an interval of the periods from 9.6 to 48 hours. Furthermore, as with the processing in the previous experiment, the spectrum of each time sequence was normalized to the maximum. The normalized spectra were averaged, and the spectrum for the time-parameter average for all-time series of Eq. (1.3.1) was obtained.

Fig. 1.3.9 shows the averaged spectra of time variations for the amplitudes and phases of monofrequency vibrosignals with the frequencies of 6.3 and 7.0 Hz, and their comparison with the gravity spectrum. Both spectra contain maxima

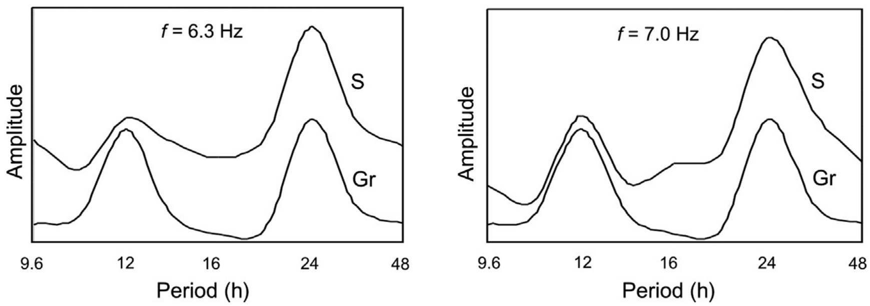

FIGURE 1.3.9

Average spectra of variations in the parameters of vibrosignals (S) and tidal variations of gravity (Gr). The signal frequency is 6.3 Hz (left), 7.0 Hz (right). The distance from the CV-100 vibrator is 356 km. Spectra have correlated maxima with periods of 12 and 24 hours for seismic and gravity data.

with periods of 12 and 24 hours, repeating the results of the previous experiment. Given the uniformity of the time series, the maxima of tidal variations for gravity were obtained. The spectral line width was determined by the overall duration of the experiment (4 days), allowing us to clearly detect daily and semidiurnal periodicity. The maxima of the variations in vibrosignal amplitudes and phases are above the general noise component of the spectrum. Estimates for 24- and 12-hour periodicity of variations in signal amplitudes give a value of 3%, and the corresponding value of the phase variations is approximately 1.5 degrees, which is close to the results of recording at a distance of 430 km.

That the same periodicities occur in the spectra of signal variations and in the Earth's tides is the major reason to suspect a relationship between them. This finding allows us to assume that the revealed variations in the vibroseismic field parameters are the result of deformation processes caused by tides, which change the velocities of seismic waves.

The obtained estimates for the amplitudes of 12- and 24-hour periodicity for the variations in seismic-signal parameters allow us to estimate the effect of the Earth's tides on the arrival times of the seismic waves and their velocities at distances of 356–430 km. At frequencies of 6–7 Hz, a change in the signal phase by 1–2 degrees is associated with a time delay of 0.5–1 ms. Characteristic propagation times of P and S waves for a distance of 356 km are about 53 and 94 seconds, respectively. Therefore the influence of the Earth's tides on the velocities of seismic waves for a distance of 356–430 km may be characterized in the results of the experiments by the relative changes of velocities $\delta V/V \sim 10^{-5}–10^{-6}$. This estimate is considerably lower than was obtained in previous experiments and is an upper estimate for the velocity variations, since in the experiments involving vibroseismic monitoring, it was impossible to exclude the influence of other varying natural factors (temperature, pressure, etc.) with daily and half-daily periodicities.

Thus, the experiments allowed us to re-evaluate, by an order of magnitude accuracy, the expected crustal effects of tidal deformation on the velocity of seismic waves.

1.3.4 Active vibroseismic experiment for Earth's crust velocity models verification

The study of the structure of the Earth's crust of the Baikal rift zone is one of the fundamental tasks of geophysics. They are associated with the study of the processes of rifting and modern geotectonics in one of the most seismically active regions of Asia (Bushenkova et al., 2002; Gao et al., 2003; Tiberi et al., 2003; Zorin et al., 2002, 2004; Zhao et al., 2006). Two modern velocity models of the Earth's crust of the south of the Baikal rift zone and adjacent areas of northern Mongolia are constructed on the basis of seismological data obtained in the international experiments BEST (Baikal Explosion Seismic Transect) and

PASSCAL (Program for the Array Seismic Study of Continental Lithosphere) (Fig. 1.3.10) (Nielsen and Thybo, 2009; Mordvinova and Artemyev, 2010; Suvorov et al., 2002).

The international experiment BEST was carried out on a 360-km profile crossing Baikal and tectonic structures of southern Baikal. Seismic data were obtained using the deep seismic sounding (DSS) technique with records of reflected and refracted waves from explosions. A two-dimensional (2D) layered velocity model of the Earth's crust and upper mantle was constructed for the Siberian platform, Baikal, and the Sayan–Baikal fold belt (Nielsen and Thybo, 2009). An important feature of the model is the presence of a high-velocity layer with a velocity of 7.2–7.3 km/s in the lower crust at the boundary with the mantle. It is located at depths from 28 to 42 km under the Siberian platform and from 32 to 46 km under

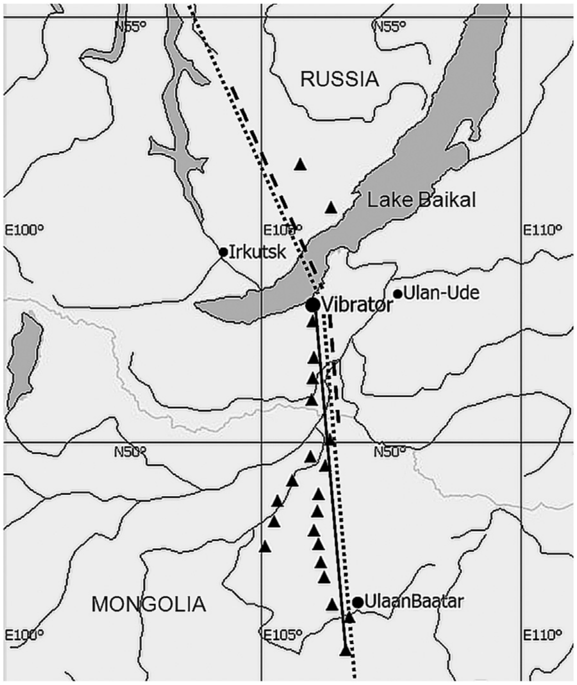

FIGURE 1.3.10

Map of the southern part of the Baikal region and northern Mongolia with seismic data recording profiles. The profile of the BEST experiment is a *dashed line*, the PASSCAL experiment profile is a *dotted line*, the vibro-DSS profile of Baikal-Ulaanbaatar is a *solid line*. The points of vibroseismic signals recording on the vibro-DSS profile are marked by *triangles*. Vibrator is a *black circle*. *BEST*, Baikal Explosion Seismic Transect; *PASSCAL*, Program for the Array Seismic Study of Continental Lithosphere; *Vibro-DSS*, Vibrational deep seismic sounding.

the Sayan–Baikal fold belt in the southern Baikal region. This layer is more than 10 km in thickness.

The international experiment PASSCAL was performed in the southern part of the Siberian platform, in the southern part of the Baikal rift zone, and in the territory of northern Mongolia on a 1000-km long profile. More than 100 seismograms of teleseismic events (earthquakes) with a magnitude of more than 5.5, with epicentral distances of 30–80 degrees (3500–9000 km) were recorded and processed. Analysis of the seismograms was made by the method of P-to-SV receiver functions with the separation of exchange transverse waves in the P-wave code (Vinnik, 1977). Based on the results of the experiments, a 2D model of the velocities of seismic waves in the Earth's crust for a 1000-km profile was constructed (Mordvinova and Artemyev, 2010). The velocity model does not have a clear layered structure. The boundaries of the layers are characterized by strong variability, there are also spotted inclusions of zones of high and low seismic wave velocities.

Analysis of these velocity models of the Earth's crust, their comparison and verification were performed at ICM&MG SB RAS using mathematical modeling and vibroseismic data obtained with a CV-100 vibrator in the Baikal region. Mathematical modeling of the full-wave fields for each model from identical sources located at the same point of the profile was performed (Kovalevsky et al., 2016).

The mathematical model of the 2D velocity model of the Earth's crust of the BEST experiment was created for the mathematical modeling of the full-wave field (Fig. 1.3.11). A modified numerical–analytical method for plane-layered 2D models of media was applied. This method makes it possible to perform calculations for ultra-long distances on long profiles. This method uses analytical transformations over spatial and time variables and numerically calculates the values of series of analytical functions (Fatyanov and Terekhov, 2011).

Mathematical modeling of the full vibroseismic field for a considerably inhomogeneous 2D model of seismic wave velocities in the Earth's crust of the PASSCAL experiment (Fig. 1.3.12) was performed at the Siberian Supercomputer Center using hybrid multicore computing systems with graphics processing units. A parallel algorithm based on finite-difference methods for solving the equations of the dynamic theory of elasticity has been developed. A modified finite-difference scheme of the fourth order of accuracy with respect to space was used (Karavaev, 2009; Karavaev et al., 2015).

Theoretical seismograms for distances of 0–400 km from the source were obtained as a result of mathematical modeling of wave fields for the velocity models of the Earth's crust using data of the experiments BEST and PASSCAL (Fig. 1.3.13). These are shown in Fig. 1.3.13, where the horizontal and vertical axes denote distance Δ from the source and the reduced travel time $T = t - \Delta/8$ km/s, where t is the travel time and 8 km/s the reduction velocity. Theoretical seismograms for the layered velocity model of the experiment BEST clearly show straight, reflected, and refracted waves with distinct arrival times and velocities

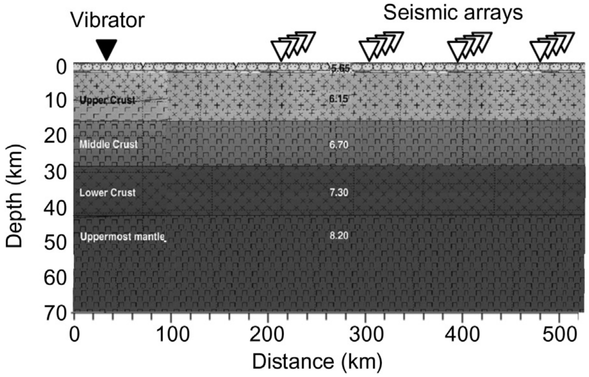

FIGURE 1.3.11

Mathematical model for the calculation of the full-wave field of the Earth's crust velocity model of experiment BEST. In the mathematical model, the layers have horizontal boundaries, which make it possible to use a numerical–analytical method. The model includes five layers with P-wave velocities of 5.65, 6.15, 6.70, 7.30, and 8.20 km/s. The average layer thicknesses and the average velocities of P-waves in the layers coincide with the initial velocity model (Nielsen and Thybo, 2009). The position of the source and the seismic arrays in the points of recording is shown on the free surface by triangles. *BEST*, Baikal Explosion Seismic Transect.

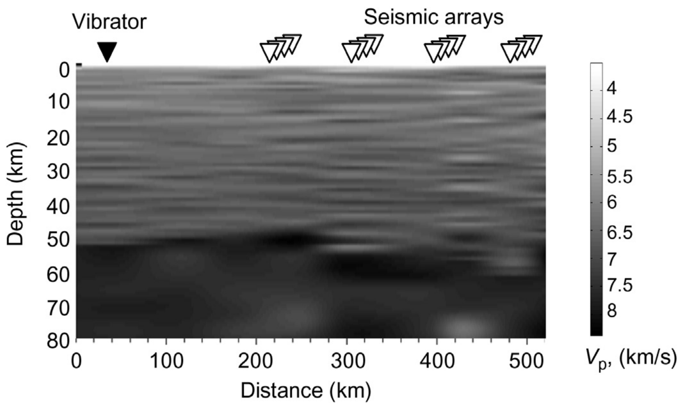

FIGURE 1.3.12

Mathematical model for the calculation of the full-wave field of the Earth's crust velocity model constructed from the data of the PASSCAL experiment. In mathematical model constructing, we used velocity section of profile stations (the results of inversion of the receiver function) from Mordvinova and Artemyev (2010). The model has an unclear layered structure and requires the application of finite-difference modeling methods. The position of the source and the seismic arrays in the points of recording is shown on the free surface by triangles. *PASSCAL*, Program for the Array Seismic Study of Continental Lithosphere.

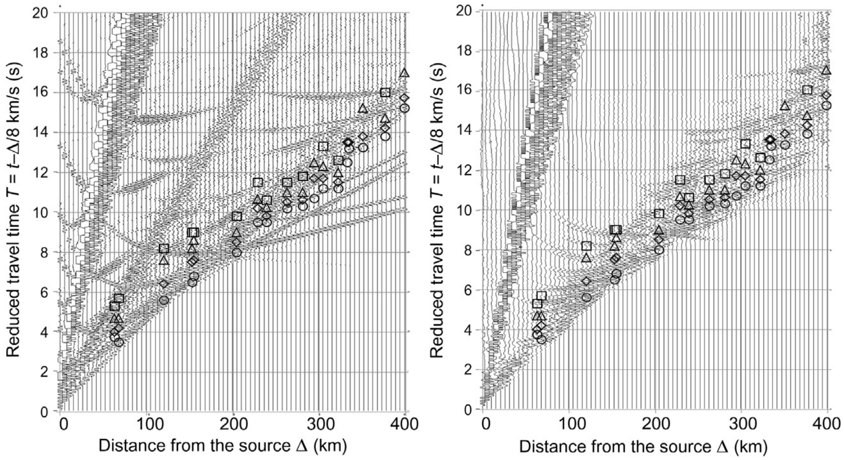

FIGURE 1.3.13

Reduced theoretical seismograms and experimental data of the P-wave arrival times for the 400 km section of the Baikal-Ulaanbaatar profile, on the left for the Earth's crust velocity model of the BEST experiment, on the right for the PASSCAL experiment. The symbols (circles, diamonds, triangles, and squares) are the arrival times of the first four waves of maximum amplitude in the P-wave group on vibrational seismograms. The horizontal and vertical axes denote distance Δ from the source and the reduced travel time $T = t - \Delta/8$ km/s, where t is the travel time and 8 km/s is the reduction velocity. *BEST*, Baikal Explosion Seismic Transect; *PASSCAL*, Program for the Array Seismic Study of Continental Lithosphere.

corresponding to the layers of the model. Waves propagating along the lower crust layer with the velocity of P-waves of 7.30 km/s have a linear hodograph at distances of 210–400 km, are the first arrivals and have a reduced time of 8–10 seconds. Refracted waves propagating along the upper mantle with a velocity of 8.30 km/s have a small amplitude and can be traced only at the first few kilometers from distances of 205 km. Theoretical seismograms for the inhomogeneous velocity model of the experiment PASSCAL have the form of extended vibration groups representing the superposition of waves. Reflected waves can be traced only at the first 150–200 km from the source.

A comparison of the theoretical and experimental vibrational seismograms in the 400-km section of the Babushkin-Ulaanbaatar profile was performed to verify the constructed models. Vibrational seismograms were obtained in vibrational DSS (vibro-DSS) works using a powerful seismic vibrator CV-100 of the South Baikal test site of SB RAS (Kovalevskiy et al., 2017). These experiments were performed by ICM&MG SB RAS and GI SB RAS (Russia) in cooperation with the Institute of Astronomy and Geophysics of the Mongolian Academy of Sciences (IAG MAS, Mongolia) in 2011–13 (Fig. 1.3.10). Small seismic arrays of 5−10 three-component sensors with digital recorders “Baikal” with a total base of 1−2 km were used for the recording of vibrational signals. The distances between the recording points on the profile were from 20 to 50 km.

The studies of the vibroseismic field of a powerful seismic vibrator CV-100 installed at the South Baikal test site were performed in the southern part of the Baikal region and northern Mongolia. At 500 km profile Baikal-Ulaanbaatar, the vibro-DSS was carried out (Kovalevskiy et al., 2017) (Fig. 1.3.10). Recording points were located on the profile from 65 km up to 500 km from the CV-100 vibrator; the distance between the recording points was from 20 to 50 km. At each recording point, small seismic arrays of 5−10 three-component sensors with “Baikal” digital recorders were used. The sensors were located linearly with the direction to the vibrator. The distance between the sensors was 200 m, the total base of the linear array was 1−2 km. These experiments were carried out at ICM&MG SB RAS and GIN SB RAS (Russia) in cooperation with the IAG MAS (Mongolia) in 2011−13.

Processing of the vibroseismic signals recorded by the small seismic arrays was carried out using the algorithms of spatial filtering of seismic data that proved to be very effective for the detection of the main wave groups (seismic phases) and suppression of noise waves. Vibrational seismograms from the CV-100 vibrator were obtained at all points of the profile. They are shown in Fig. 1.3.14 for the distances of 205, 241, 294, and 377 km from the source.

A feature of vibrational seismograms is that the arrival times of waves correspond to the maxima in the vibration groups. Therefore the Hilbert transform and graphic means of displaying the current amplitudes of the seismograms were used to visualize and analyze the vibrational seismograms (Fig. 1.3.14). This made it possible to extract wave maps of P-wave sections on the vibrational seismograms and determine the arrival times. The arrival times of the first four waves in the P-wave group as experimental data are noted on the reduced theoretical seismograms for the velocity models of the BEST and PASSCAL experiments (Fig. 1.3.13). They correspond to the arrival times of waves with the greatest intensity in the group of P-waves on the vibrational seismograms.

Comparison of theoretical seismograms of the BEST experiment and data of the P-wave arrival times on experimental vibrational seismograms on the 400 km section of the Baikal-Ulaanbaatar profile showed that the arrival times of the waves with maximum amplitude correspond to hodographs of the waves with velocities of 6.15−6.70 km/s, characteristic for the layers of the upper and middle crust of the velocity model (Fig. 1.3.11). At the same time, the experimental data do not contain arrival times corresponding to waves with the velocity of P-waves $V_P = 7.25$ km/s associated with the layer having a thickness of about 10 km in the lower crust for the BEST experiment model.

The experimental values of the arrival times of waves in the P-waves group on vibrational seismograms are in the zone of the times of arrival of waves on the theoretical seismograms of the PASSCAL experiment throughout the 400 km profile. This indicates a good definition of average wave velocities in the PASSCAL

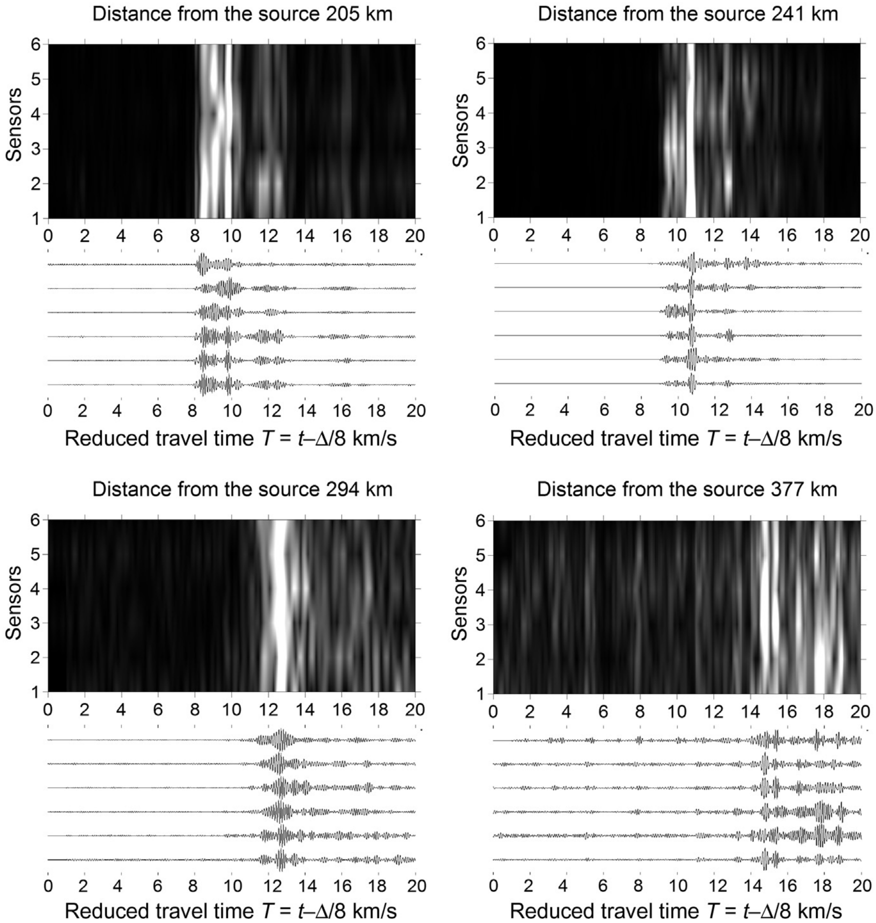

FIGURE 1.3.14

Vibrational seismograms for the 500-km profile of Baikal-Ulaanbaatar at distances from the source of 205, 241, 294, and 377 km. Graphic representation of amplitudes in the P-wave group using the Hilbert transform at the top and vibrational seismograms at the bottom. White color corresponds to the maximum amplitude of the waves, and black minimum. Vertical sensor number, horizontally reduced time $T = t - \Delta/8$ km/s, where t is time. The vertical and horizontal axes denote sensor number and the reduced travel time $T = t - \Delta/8$ km/s, where t is the travel time, Δ is a distance from the source, and 8 km/s is the reduction velocity.

experiment velocity model. It should be noted that the experimental values of the arrival times of the first wave in the group of P-waves are in good agreement with the times of the first arrivals on the hodographs of the theoretical seismograms in the range of distances from 65 to 380 km from the source.

1.3.5 Conclusion

We have determined the sensitivity of an active seismic monitoring system using powerful (100 ton) vibrators. Our experiments have shown that such a system enables us to detect variations in seismic wave velocities on the order of 10^{-5}–10^{-6}, in a 300–400 km area around a source. We investigated the influence of the Earth's crust tidal deformations on the order of 10^{-7} on the amplitude-phase characteristics of seismic waves radiated by the vibrators. We thereby determined that the influence of the Earth's tides on the velocities of seismic waves for a distance of 356–430 km may be characterized by the relative changes of velocities $\delta V/V \sim 10^{-5}$–10^{-6}.

A vibroseismic monitoring system of a 550 km × 250 km region (about 100,000 km^2) was created in the Baikal seismic zone on the basis of the powerful seismic vibrator CV-100 of the South Baikal test site of SB RAS, mobile recording complexes, and the seismic stations of the regional network. The use of data from these stations made it possible to organize continuous monitoring of the Baikal seismic zone using periodic radiation sessions of sweep signals and monofrequency signals from the vibrator. The results of these works can be used in solving the problem of medium-term forecast of earthquakes in seismically active regions. Since 2003, the Buryat Branch of the Geophysical Survey RAS and GIN SB RAS, Ulan-Ude, have been engaged in continuous vibroseismic monitoring using seismic stations of the regional seismic network. The stationary regional seismic stations of the Buryat and Baikal Branches of the Geophysical Survey SB RAS and mobile seismic recording systems of ICM&MG SB RAS and GIN SB RAS are used. The monitoring area is 550 km × 250 km in the southern part of the Baikal region.

The theoretical seismograms are compared with data from the P-wave arrival times on experimental vibrational seismograms over a 400-km section of the Baikal-Ulaanbaatar profile. The theoretical seismograms were obtained by the methods of mathematical modeling of wave fields for the Earth's crust velocity models of the experiments BEST and PASSCAL. The vibrational seismograms were obtained by measuring the vibroseismic wave field of the CV-100 vibrator at the South Baikal test site of SB RAS. The values of the arrival times in the P-wave group in vibrational seismograms correspond to the values in the theoretical seismograms for waves of large amplitude. Waves of small amplitude in the first arrivals were detected in the experimental vibrational seismograms not at all distances from the source.

Vibroseismic seismograms at different points of the profile have high repeatability due to the high stability of radiation of sweep signals by the vibrator and the use of small seismic arrays in the recording of vibrational signals. This makes it possible to use the accumulation of repeating identical radiation sessions to increase the signal-to-noise ratio and perform spatial filtering to detect weak waves. These properties make the powerful seismic vibrator the most suitable source for verifying velocity models of the Earth's crust in comparison with powerful explosions.

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