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Creation of a technology of calibration and traces using powerful seismic vibrators

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Efficiency of systems for monitoring of nuclear tests within the Comprehensive Test Ban Treaty (CTBT) essentially depends on accuracy in the determination of time, geographical coordinates, depth and power of explosions in accordance with the data for seismic waves recorded by seismologic stations. The purpose of the present project is to develop a technology of calibration of seismic arrays and seismic stations of the International Seismic Monitoring System (ISMS) using powerful vibrators. This make it possible to increase accuracy in the determination of the coordinates of explosions.

Errors in the determination of the parameters of a seismic source by a network of ISMS stations are due to horizontal and vertical inhomogeneity of the Earth's crust and upper mantle. This inhomogeneity causes large variations in the parameters of seismic waves, that are recorded at various azimuths and distances from a source. Deviations of wave arrival times and amplitudes recorded by a seismic array from standard hodographs and calibration curves averaged over azimuths cause calculation errors of the source parameters.

Powerful 100-ton seismic vibrators, seismic waves from which are recorded at distances of 1000 km, have been developed in the Siberian Branch of RAS. It is proposed to carry out investigations to compare explosive (explosions in quarries) and vibrations seismograms and study the possibility of using powerful vibrators for calibration of the ISMS network of stations.

At the first stage of experimental works, quarries with regularly set off industrial explosions, seismic waves from which are recorded at the Bystrovka vibroseismic test site (Novosibirsk region), will be chosen.

At the second stage, it is proposed to perform observations of the vibroseismic field from powerful vibrators in the chosen quarries at distances not exceeding 500 km. They are determined by the capabilities of the vibrators mounted at the Bystrovka test site.

In the process of project realization, numerical simulation will be made to study seismic waves caused by short-delayed explosions in quarries, in particular, to compare wave fields under explosive and vibrational excitation.

The peculiarities of propagation of seismic waves near the Earth's surface and the influence of reflected waves on the accuracy in the determination of the angle of an arriving wave recorded by a borehole seismometer will be investigated theoretically and experimentally. A method for determination of the corresponding corrections will be developed.

Processing of obtained materials will make it possible to identify the main features of explosive and vibrational seismograms, estimate the power of vibrators, that is necessary for calibration of seismic stations at distances of up to 2000 km, and develop a method for calibration taking into account regional inhomogeneity.

1. Introduction

This accuracy affects the reliability of identification of seismic events (nuclear explosions) and the choice of methods and instrumentation of monitoring systems in places of expected explosions. Creation of a Global Network of Seismic Stations (GNSS) is planned within the framework of the International Seismic Monitoring System (ISMS). GNSS includes 50 small seismic arrays (Alpha stations) and 100 three-component seismic stations (Beta stations). The network is dense and geographically uniform and will provide continuous seismic monitoring and high accuracy in identification of low-power seismic events for international inspections in places of possible nuclear tests.

Accurate determination of the parameters of a seismic source by GNSS is complicated mainly due to considerable horizontal and vertical inhomogeneity of the Earth's crust and upper mantle. This inhomogeneity causes large variations in the parameters of seismic waves, which are recorded at various distances of the stations from a source and at various azimuths of their location relative to the source. Deviations of wave arrival times and amplitudes recorded by a seismic network from standard (global or regional) hodographs averaged over azimuths and from one-dimensional calibration curves determine calculation errors of the source parameters.

These errors depend on such factors as relative location of a source and of a seismic array; location of stations of the network in different geological provinces or strongly varying conditions of the medium's upper part. A general dependence of the errors on these factors can be described, only if the Earth's structure in the regions of source location, the "source – station" seismic traces, and all station locations are known in detail. In this case, the direct and inverse dynamic problems of seismology can be solved numerically. Present-day data for the three-dimensional structure of the Earth's crust and upper mantle are, however, insufficient for this purpose. Therefore, each situation must be considered separately, using both the available information on the Earth's structure in the region being considered and the empirical estimates of the Green tensor obtained with the help of calibration measurements in a source-seismic network.

Beginning in the 50-ies for oil geological prospecting and in the 60-ies for nuclear tests monitoring, a large number of works have been carried out using the Method of Deep Seismic Sounding (DSS) [1, 2, 4, 5, 6] and the method of profile seismologic observations [3] in the USSR and USA [7–9].

In accordance with the data of Russian and American geophysicists [5, 6, 9], variations in the hodographs of first arrivals in the crust and mantle can reach 4–5 s at distances of more than 1200 km from a source depending on the type of geological province and the azimuth to the epicenter [6]. Variations in the amplitudes with distance and the azimuth to the epicenter are even more appreciable. Variations in the amplitudes can be 1–2 orders of magnitude at distances of 1200–1800 km for different geological regions. They can increase up to 2–3 orders of magnitude, if a source and a recording station are in different geological regions and in different surface conditions.

The well-known global hodographs of Jeffries–Boolen, Gutenberg, Herrin averaged over regions and the unified calibration curve of amplitudes are usually used in seismology. In practice, however, it is difficult to use, in addition to these averaged laws, more accurate information about the influence of regional features of the structure of the Earth's crust and mantle on wave times and amplitudes in estimating the coordinates and energy characteristics of explosions. In this case, errors in the determination from seismic data of explosion times of 1–2 s, in the determination of epicenter coordinates of 50–80 km and in the estimation of explosion power of 50–100% are frequent. Therefore, multidimensional hodographs and amplitude curves should be used. Even if corrections to wave times and amplitudes for real traces, kinematic and dynamic corrections for seismic stations are simply taken into account, there can be an increase in the accuracy of determination of the time, coordinates and power of explosions by 30–40% in most unfavorable combinations of "source – receivers" under considerable horizontal inhomogeneity of the Earth's structure. Such corrections are determined from the results of calibration of seismic traces and seismic stations, that are usually made now, after prohibition of nuclear tests, using industrial and special geophysical explosions.

In the development of the calibration technology of seismic traces under considerable horizontal and vertical inhomogeneity of the Earth's crust and upper mantle, mathematical simulation of full seismic fields for these media and understanding of occurring wave processes is important. For example, at a certain layer width-wavelength ratio the first arrivals of waves can be lost and the so-called "screened" wave can be recorded, when a refracted wave passes through a thin high-velocity layer in the Earth's crust.

This process must be taken into account in calibration of traces [10]. Three-dimensional numerical simulation is an effective instrument in modeling of industrial explosions and investigation of wave processes occurring in this case.

An important problem is theoretical and experimental investigation of the peculiarities of propagation of seismic waves near the Earth's surface and the influence of reflected waves on the accuracy in the determination of the angle of an arriving wave recorded by a borehole seismometer.

Industrial explosions, due to their special character (short- and long-delayed), do not make it possible to obtain repeated seismograms, even in case of successive explosions in one mine. They give considerable variations in the dynamic characteristics of seismograms, but similar kinematic characteristics. Therefore, the recording distance of even powerful industrial explosions (100–200 tons) cannot exceed 400–500 km. Special geophysical explosions have better metrological characteristics. Their wide use for calibration of seismic traces is, however, limited due to their high cost and ecological requirements.

The purpose of the present project is to develop a technology for calibration of seismic traces and seismic stations with the help of sounding signals with precise metrological characteristics. Such signals can be obtained from powerful vibrators, whose amplitude, frequency and time are controlled.

The project will provide conditions for conversion of the scientific-technical potential of some institutes and organizations of the Siberian Branch of the Russian Academy of Sciences, that took part in the development of observation and monitoring methods of nuclear explosions. It gives prospects for employment and professional improvement, provides possibilities for applications in the civil sphere of the experience and knowledge of highly qualified scientists and specialists, who were previously working at military applied programs.

Scientists and engineers of the Siberian Branch (SB) of RAS have accumulated rich experience in the observations, analysis and modeling of seismic signals from nuclear explosions at the Semipalatinsk and Novaya Zemlya Test Sites in the Former Soviet Union (FSU), Loch-Nor in China and the Nevada Test Site in the USA, earthquakes in the Altay–Sayan region and neighboring regions.

Development of a new method – active seismology – was first initiated in the Siberian Branch of RAS. Here, powerful seismic vibrators are used for vibroseismic sounding of the Earth's crust and upper mantle.

The Siberian Branch of RAS has considerable scientific-technical potential to achieve the objectives of the present project. Over the last 15 years, some powerful low-frequency vibrators with a force of up to 100 tons and a frequency range of 2–15 Hz have been developed and created. Numerous experimental investigations of seismic fields from vibrational sources at distances of up to 1000 km has been carried out. The metrological foundations of vibroseismic sounding using powerful low-frequency vibrators have been developed.

The CV-100 vibrator is the most powerful vibrational source. It creates a vertically oriented force with an amplitude of 100 tons by synchronously rotating debalances, which are mounted on a platform. The use of the radiation regime near the resonant frequency of the "vibrator – ground" system in a region of 7 Hz makes possible a manifold increase in the radiation power.

In experiments with this source, vibrational seismograms at distances of 320 km and records of monochromatic signals at distances of up to 1000 km have been obtained. The vibrator CV-40 of similar type is transportable. It develops actions of 40–50 tons. Its working frequency range is 5–15 Hz. The hydroresonant vibrator HRV-50 creates a force with the help of vertically oscillating water volume with a mass of 60 tons in a frequency range of 2–10 Hz. The source can be scaled to create vibrators with an action of several thousand tons. A variant of such a vibrator for actions of up to several thousand tons has been developed recently. It utilizes rocket shafts, which are no longer used due to disarmament.

Powerful seismic vibrators make it possible to determine, with a high degree of accuracy, corrections to wave travel times and amplitudes. This can be done by analyzing vibrational seismograms, that are obtained, when a vibrator radiates oscillations in a wide frequency range. Signals with frequency modulation (sweep signals), that are phase-modulated or noiselike, i.e., those described by a narrow correlation function can be used as such oscillations. In this case, a vibrational seismogram (an analog of the pulsed seismogram) is reconstructed at the recording point as a result of correlation of long seismic signals with the recorded signal. A seismogram obtained in such a way represents the main types of seismic waves whose characteristics can be measured.

High stability and ideal recurrence of radiated signals is an important metrologic advantage of using vibrators for calibration. This makes it possible to obtain identical seismograms at a recording point for their subsequent statistical processing to increase accuracy in the determination of calibration characteristics. In contrast to explosions, vibrational sources are safe for the environment. They enable calibration of seismic traces from any region.

Numerous experiments on vibroseismic deep Earth's sounding, that have been conducted in the Siberian Branch of RAS over the last 15 years show that development of a technology of calibration of seismic traces and seismic stations with the help of powerful seismic vibrators is justified.

Theoretical and experimental works with powerful seismic vibrators are being continued now. Some of these experiments are devoted to detection of changes in the tensely deformed state of the medium caused by lunar-solar tides. In the 1997 field season, it is planned to continue these works, that were initiated in 1996 at observation stations at distances of 430 and 520 km. In these experiments, a relation between the time variations in amplitudes and variations in the gravitational force during lunar-solar tides has been detected. The purpose of the 1997 experiments is to determine sensitivity of various types of waves to variations in the tensely deformed state of the medium. The methods and distance scales used in these works are consistent with the objectives of the proposed project on calibration of seismic traces with the help of powerful vibrators.

2. Technical approach and methodology

The coordinates of sources of seismic waves can be determined with a low accuracy, if a sparse network of stations located far from the epicenter of an event is used, and the velocity structure of the medium is not known. Investigation of the velocity structure of entire regions is labor-consuming and expensive. When such information is absent, accuracy in the determination of the coordinates of sources can be increased by calibrating the territory with respect to a recording station and by compiling a map of corrections to determine the coordinates of the source.

The purpose of the present project is to develop a method for calibration of a seismologic station or array using powerful vibrational sources, consider alternative calibration methods using industrial explosions and earthquakes and analyze the capabilities of the vibrational approach in comparison with the other two calibration methods.

Calibration by industrial explosions is a conventional approach to calibration of stations used in seismology. This approach is taken as a standard for comparative analysis of the capabilities of vibrational calibration of seismologic stations by determining the coordinates of epicenters.

It is planned to carry out the following investigations to develop a vibrational method for calibration of stations on the basis of 3D modeling:

- study of wave fields created by a vibrational source at distances of up to 500 km;
- comparison of wave fields from vibrators with wave fields from explosive sources;
- investigation of stability of the dynamics of waves excited by industrial explosions and vibrators.

The following tasks will be solved:

- it will be proved experimentally that seismic signals from vibrators can be recorded at distances of up to 500 km;
- data on similarities and differences of wave fields from pulsed and vibrational sources will be obtained and the accuracy in determination of times in vibrational investigations will be estimated;
- stability of wave dynamics under the vibrational excitation and industrial explosions distributed in space and time will be estimated;
- estimates of the accuracy of individual measurements in calibration of stations will be obtained from a combined analysis of the data of industrial explosions and vibrators.

Similarities and differences of wave fields from explosions and vibrators will be investigated. This investigation will be based, first, on an analysis of the available materials, when areas of wave groups passage and their dynamic and kinematics characteristics are considered on the whole for the region and similar characteristics of vibrational seismograms are compared. Second, seismograms obtained in interchangeable "source – receiver" points will be compared. In this case, recording of industrial explosions will be made near a vibrator, and recording of signals from this vibrator – in the vicinity of a quarry. Such comparisons with time records make it possible to prove that wave arrival times in vibrational and explosive seismograms are identical and allow a more correct comparison of wave fields.

For this experiment, a seismologic station must be located near a vibrator. It must work in an "expectation" recording regime of seismologic events. The data of this station will serve as original material for selection of quarries with subsequent recording of signals from vibrators and explosions at interchangeable points. Quarries at different distances from a vibrator will be chosen on the basis of the data of this station. Recording of good-quality seismograms can be made at them. Recording of signals from the vibrator in these quarries and of explosion times in them will be made at the next stage of the experiments. The influence of the source on recorded wave fields with different parameters of explosions (charges, delays, configuration of charges in the area) will also be compared on the basis of an analysis of records. The dynamic stability of wave fields from industrial explosions will be investigated and compared with the stability of vibrational wave fields. It will also be investigated on the basis of solving the direct dynamic problems. Theoretical wave fields of models of sources of vibrational and industrial explosions will be constructed for a cross-section of the Earth's crust in the region under investigation. The differences and agreement of the theoretical calculations with the experimental data will be considered. This analysis will make it possible to gain a better understanding of the capabilities of the both approaches to calibration of stations using vibrators and industrial explosions.

In comparison to works of the previous years, larger groups of devices and a technology of seismogram summation from many vibrational actions will be used in the experiments on recording of signals from vibrators at large distances. Summation of multiple vibrational actions will be made, whereas previously only seismograms of single actions lasting approximately 1 hour were considered.

Methods for calibration of stations will be compared using the Altai–Sayan region as an example. To do this, a map of areal distribution of industrial explosions will be compiled, the accuracy of areal calibration of the region will be estimated, and a comparison with vibrational sources will be made.

One more comparison of the accuracy of calibration will be made with seismologic materials of the regional network. For this, the coordinates of sources determined by local stations are compared with the coordinates obtained by a remote station.

A map of corrections will be compiled on the basis of this comparison. The accuracy of this map depends on the accuracy of determination by a local network of stations, areal distribution and the number of earthquakes in this region. At the final stage, the question of spacing between excitation points in the area for calibration of stations depending on the region's structure and the influence of this spacing on the accuracy of calibration of the region on the whole will be considered.

Besides, theoretical and experimental investigations of the peculiarities of propagation of seismic waves near the Earth's surface and the influence of reflected waves on the accuracy in the determination of the angle of an arriving wave recorded by a borehole seismometer will be made.

Methodological recommendations for calibration of seismic stations, traces, and seismologic arrays using vibrators will be made on the basis of the results of the investigations.

3. Expected results

The following results will be obtained:

- wave fields excited by industrial explosions and powerful vibroseismic sources will be compared to determine the first arrivals and dynamics of waves;
- a method for high-precision calibration of seismic stations and seismic traces using powerful vibrators will be developed;
- the accuracy of calibration by explosive and vibrational methods will be compared.

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