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Long-Term Seismological Sea-Bottom Monitoring Using Autonomous Bottom Stations

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Abstract—Merits and demerits of recording of seismic signals at the bottom of water areas are considered. It is shown that long-term seismological monitoring systems should be placed in the regions of industrial development of the shelf and continental slope and in the areas of high seismic and tsunami hazard of oceans and seas. The results obtained during expeditions of the Shirshov Institute of Oceanology of the Russian Academy of Sciences with the use of broadband bottom seismographs are reported. Autonomous bottom seismographs with long-term operation at the bottom and operative communication via satellite and radio channels are proposed for the formation of a marine seismological network.

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Key words: broadband bottom seismographs, marine seismological network.

INTRODUCTION

At present time, the developed land seismological network covers practically all the continents. It includes modern broadband seismographs for recording of various seismic events and solving numerous research and application seismological problems. At the same time, according to the estimates available, over 80% of earthquakes occur under the ocean and sea bottom. Land seismographs record signals of the remote marine earthquakes with substantial distortions and miss signals of the weak earthquakes. For this reason, it is impossible to estimate adequately the tectonic processes occurring in the Earth's interior in their unity and variety. Also, the deep structure of the ocean crust and the superior mantle are unstudied.

Marine seismographs should be used for studying the sources of microseism generation and regularities of their propagation in the ocean, occurrence and development of tsunamis, seismic activity in subduction zones, mid-ocean ridge areas, and other regions. Since the level of seismic noise at the bottom is much lower than that overland on average, seismic activity of a sea region can be estimated for shorter period of time [Levchenko, 2002; Ostrovskii, 1998; Solov'ev, 1985, 1986].

As a result of the intense development of hydrocarbon deposits at the shelf and continental slope and pipe and cable laying, the bottom earthquakes and the related phenomena become extremely hazardous for the marine structures and ecology of the regions in general. Because of the absence of the marine seismological network, seismicity of water areas and, consequently, potential danger for shore structures and populated areas are underestimated. Also, it seems important to study the effect of the close and remote earthquakes on flow rates [Solov'ev, 1986; Lobkovskii et al., 2005]. Therefore, seismological securing the marine oil- and gas-production complexes and other big shore and submerged structures is required. The formation of an integrated seismological system of recording and processing of the earthquake signals and search for their possible precursors which would unite the land and marine networks has acquired vital importance. However, for some objective and subjective reasons, so far there has been no the marine seismological network [Levchenko and Matsievskii, 2000; Araki and Suyehiro, 2001].

In our opinion, the main difficulties preventing the formation of the marine seismological network are the following. Since the bottom stations operate in the automatic regime, they should be highly reliable during long period of time. The stations should have crash-proof casings for preventing the instrumentation from depth pressure and shocks of a ship board

†Deceased.

and firm bottom during placing on recording. There are practically no commercial seismic sensors which could operate on the bottom stations and had the metrological parameters close to those of the land seismometers. Also, it is difficult to provide long-term power supply of the instrumentation and transmission of seismological information to the shore [Sutton and Duennebier, 1987; Levchenko, 2001].

A principal solution of the problem could be the use of submarine cables for feeding the bottom stations, control of their operation, and direct information transmission to the shore. However, the submarine cable installation is extremely expensive. The promising trend seemed to be connection to the existing overseas bottom communication cables, which currently are not used for their direct purpose (VENUS, POSEIDON, and GEO-TOK projects). However, such projects also require substantial investments. In addition, old submarine cables have low strength and watertightness upon pulling-out and reutilization. Therefore, there are few stationary marine seismographs with cable connection to the shore. All of them are located in Japan and placed relatively not far (100–200 km) from the shore [Kasahara and Toshinori, 1997; Kasahara et al., 2003; Mikada et al., 2003].

Since the stationary marine seismological network is currently absent, autonomous bottom seismic stations (ABSS) are mainly used. They do not solve all the existing problems; nevertheless, the ABSSs have some advantages over the cable stations. High mobility of the ABSSs allows fast deploying the station network in any World Ocean region of interest. Any polygon configuration in accordance with the specific problems and instrumentation available can be chosen. Instrumentation composition and parameters of seismometers can vary prior to the installation. Finally, the ABSSs are less expensive than the stationary cable stations by orders of magnitude. The autonomous bottom seismic stations are available in the USA, Russia, Japan, German, and France; however, the main metrological parameters of the stations are, as a rule, worse than those of the best land models [Wielandt and Steim, 1986; Jacobson et al., 1991; Rykov, 1995; Levchenko, 2001; Shiobara et al., 2001; Zubko et al., 2003].

Considering the aforesaid, one cannot, however, discount the substantial scientific and engineering achievements in the field of marine instrument making, hydroacoustic and satellite communication, electronics, and computer techniques, which allow, to a great extent, overcoming the mentioned difficulties. Furthermore, one can state that the stationary marine seismological network whose metrological characteristics would approach those of the land network can be formed in foreseeable future with reasonable expenses.

Also, it must be noted that at recording of the seismic signals at the bottom certain systematic problems arise, such as probable distortions during installation of a seismograph at the soft bottom, near-bottom current noise, and features of propagation of the seismic signals and microseisms in the ocean. At present, these problems are successfully solved by marine seismologists using the achievements of hydroacoustics, hydrophysics, and novel numerical simulation and experimental results [Bradner et al., 1970; Kasahara et al., 1980; Duennebier et al., 1981; Trehu, 1985a; Kontar et al., 1991; Jacobson et al., 1991; Levchenko, 2001].

In our opinion, the development of the marine network should begin with the so-called hot points. First of all, it is the regions of marine oil and gas deposits. The hot points in Russia are the Barents, Pechora, and Kara Seas in the north, the Black and Caspian Seas in the south, and the Sea of Okhotsk in the east. The cable bottom seismographs can be integrated in the ecological monitoring network which should deploy around each drilling or producing platform. In addition to monitoring of seismicity, including that caused by redistribution of tectonic stresses during production, this network can solve other problems, such as supplementary exploration and estimation of reserves. A data collection post placed on a platform would provide operative information transmission and the conditions required for information processing [Shiobara et al., 2001; Mikada et al., 2003; Lobkovskii et al., 2005].

Also, local seismologic networks should be primarily deployed in "seismic gaps" where the strong sea earthquakes and tsunamis can be expected. This is, for example, the Avachinsk Bay in Kamchatka and the south and central parts of the Kuril Islands. Because of considerable remoteness from the shore, the long-term autonomous bottom stations with operative express-information transmission should be installed there. The main tools of such stations should be a broadband seismograph, a strong-motion seismograph, an operative data analyzer, and a satellite or radio communication system.

INSTRUMENTATION FOR RECORDING OF THE SEISMIC SIGNALS AT THE BOTTOM

The autonomous bottom seismographs available in a number of developed countries, such as the USA, Japan, Germany, and France are intended, as a rule, for marine exploration seismology and solving specific seismological problems, for example, determination of seismicity of some water areas. For this reason, such seismographs have limited characteristics as compared to those of land seismographs, in particular, lower frequency band, lower channel sensitivity, and shorter operation time (usually not longer than two–three weeks). Therefore, long-term monitoring of water areas requires the qualitatively different bottom seismic stations whose parameters would be close to those of the land stations.

A limited recording frequency band of the marine seismographs is related, first of all, to the absence of reliable compact economical broadband seismic sensors. In the high-quality land instrumentation, pendular seismic sensors are currently used (Streckeisen, Switzerland and Guralp, England) with a frequency band from 0.01 to 20 Hz. They are big and heavy, require manual installation, and fear of shocks and moisture. In the autonomous bottom seismographs, compact sensors with a frequency bands from 2–3 to 20 Hz are mainly used. They do not record surface low-frequency Rayleigh and Love waves and low-frequency bottom vibrations caused by tsunamis.

For more than twenty years, in the broadband bottom seismographs of the Institute of Oceanology of the Russian Academy of Sciences (IO RAS), EKhP-17 electrochemical seismic sensors have been used developed at the Institute of Electrochemistry of the Russian Academy of Sciences [Abramov and Graphov, 1978; Levchenko et al., 1994]. The main advantages of the electrochemical seismic sensors are low shock sensitivity (up to 30 g), possibility of operation at any slope, small dimensions and weight, and economical feed. The known shortcomings of the electrochemical seismic sensors, such as some temperature and external pressure dependence of the parameters, are inessential for the bottom seismographs and now successfully overcome constructively.

The main metrological characteristics of the broadband bottom seismographs of the IO RAS were determined by long bench testing. In 1993, the EKhP-17 electrochemical seismic sensors were certified at the Laboratory of Geophysics of the National Research Institute for Physicotechnical and Radio Engineering Measurements (VNIIFTRI) of the State Committee of the Russian Federation for Standardization, Metrology, and Certification. Such parameters as a conversion coefficient, a transversal sensitivity coefficient, temperature dependence of the conversion coefficient, and intrinsic noise were determined. The measurements were performed in the frequency band 0.01–30 Hz on a VU-2 standard certified vibration table [Levchenko, 2001].

The broadband digital bottom seismic station of the IO RAS and its software were tested and adjusted for long periods of time from March till August 1994 and from May 1996 till April 1998 at the Laboratory of Seismometry of the Institute of Physics of the Earth of the Russian Academy of Sciences (IPE RAS). During testing, several hundreds of regional earthquakes and several teleseismic events were recorded. During signal processing, energy spectra, coherence functions, typical periods and amplitudes of vibrations, and day and night noise spectra were determined.

Figure 1 depicts generalized amplitude–frequency characteristics of SDE model seismic sensors of the IPE RAS (curves *a* and *b*), the tested EKhP-17 seismic sensor of the IO RAS (curves *c* and *d*), and a C1014 model piezoelectric accelerometer of the VNIIFTRI. It should be noted that the frequency characteristic of the bottom seismograph was chosen with regard of the substantial growth of a bottom microseism level at frequencies below 0.02 Hz (up to 40 dB per decade). If the seismograph had a uniform frequency characteristic, the most part of its dynamic range (approximately, 60 of 120 dB) would be occupied by low-frequency noise which prevent recording of the weak earthquakes. In view of the aforesaid, in order to increase the actual dynamic range, sensitivity of the seismic sensors in the low-frequency range is reduced approximately proportional to the growth of the seismic noise level. At the same time, excessive reduction in the low-frequency part of the band is unacceptable as in this region low-frequency microseisms and the surface Love and Rayleigh waves from the remote earthquakes are recorded [Levchenko et al., 1994 and Rykov, 1995].

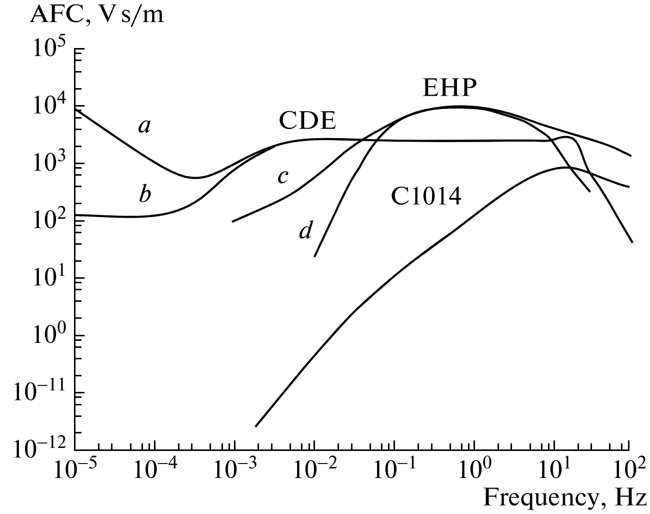

Fig. 1. Amplitude–frequency characteristics of an SDE-type pendular seismic sensor developed at the IPE RAS (curves *a* and *b*), an EKhP-17 electrochemical seismic sensor (curves *c* and *d*) developed at the IO RAS, and an S1014 piezoelectric accelerometer developed at the VNIIFTRI.

The testing results showed that the developed instrumentation and programs of the broadband bottom station provide recording of the seismic signals from the local, regional, and remote earthquakes within the frequency range from 0.05 to 25 Hz. At lower frequencies (up to 0.05 Hz), recording of the signals was difficult due to the high external noise level in the region where the IPE RAS is placed. Total feed power required for the bottom complex was 0.8 W.

The intrinsic noise level of the electrochemical seismic sensors was estimated during processing the data on microseism recording at the bottom of the Atlantic Ocean in October 1991. The microseism spectrum maximum at a frequency of 0.17 Hz was 3.6×10^{-7} m/s^2 (Hz)$^{1/2}$. At the frequencies from 0.03 to 0.12 Hz, the spectrum minimum is located which is lower than the maximum by 30 dB. This is the estimate of the sum noise consisting of microseisms and intrinsic noise of the seismic sensor and input noise of an amplifier. Consequently, the level of spectral density of

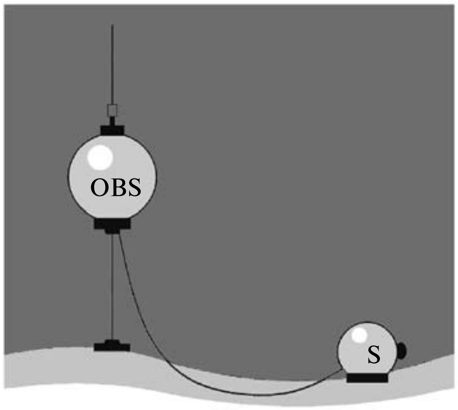

Fig. 2. Installation of the broadband autonomous seismograph of the IO RAS at the bottom.

the intrinsic noise of seismic sensor in this region should be lower than 10^{-8} m/s^2 (Hz)$^{1/2}$.

Recently, novel EP105OBS and CME411 broadband molecular kinetic (a kind of electrochemical) seismic sensors have been developed by an EENTEC company (USA) and the Center of Molecular Electronics of the Moscow Institute of Physics and Technology. At present, these detectors are being experimentally tested in the Experimental Design Bureau of Oceanologic Engineering of the Russian Academy of Sciences (EDB OE RAS).

Duration of continuous recording of the seismic signals by the autonomous seismographs depends on recorder memory volume, power source capacitance, and stability of quartz clock required for binding a seismic event to the universal time. Modern digital instrumentation and solid-state memory elements allow recording of the seismic signals along three channels and a hydrophone channel in several months if overall dimensions of a seismograph casing are acceptable. Relative instability of the clock must be not worse than 10^{-8}. This accuracy is provided by oven-controlled crystal oscillators; however, the thermostat consumes much energy. Therefore, other ways need to be used here, for example, digital compensation of a temperature error of quartz. In this case, temperature corrections can be introduced with very high accuracy determined by a temperature measurement error and an error of the correction table only. Temperature can be measured with a quartz thermometer; the correction table has to be determined for each quartz thermometer and stored in computer memory [Levchenko et al., 1987 and Zubko et al., 2003].

The obtained estimates and experimental results showed that if in a reference generator the high-precision quartz resonator is used which has two-rotation cut at a frequency of 10 MHz on the seventh mechanical harmonic, the first extremum temperature of about 10–15 °C, and aging of not more than 10^{-10} per year and a quartz resonator of thermosensitive Y cut is used as a temperature sensor, then the quartz generators with digital compensation of the temperature error that operate within the temperature range 0–10°C can provide a frequency drift of not worse than 10^{-9}. This is quite acceptable for the bottom seismographs. The developed quartz clock with digital compensation of the temperature error was subjected to long-term laboratory and full-scale testing as a part of an ABSS-1 station during seismic works in the Indian Ocean in 2004 and 2005.

For several years, special digital systems for seismic data sampling and recording have been developed for the broadband bottom seismographs of the IO RAS and EDB OE RAS. The main specific requirements on these systems are related to the necessity of signal recording in wide frequency and dynamic ranges with small amplitude and phase distortions, long-term operation at small overall dimensions and weight, high stability of the electron clock, high feed economy, and prevention of vibration noise (the absence of engines, mechanical relays, and disc drives). In all the systems, three recording regimes are provided: continuous, start-stop with a set program, and start-stop with signal-level control [Levchenko and Matsievskii, 2000; Levchenko, 2001].

In 1994, a digital recorder was developed for operation in the frequency range from 0.003 to 10 Hz with recording on a hard drive (flash memory). It was based on a V-25 microcomputer (Tern, USA) with an inbuilt multichannel AD converter. For broadening the dynamic range, recording was performed at two levels with automatic sensitivity switching, which made it possible to obtain the total dynamic range up to 110 dB. The system was a firmware complex for an Intel-compatible processor family equipped with instruments for adjustment, testing, and visualization. In 2003, a novel digital recorder was developed which contained a 24-bit sigma-delta AD converter, an ATMEGA128L controlling microprocessor, solid-state energy-independent memory up to 2 GB, and an exact time block with digital compensation of a temperature error. Total power consumption of the recorder is about 0.5 W. The recorder was subjected to full-scale testing during seismic works in the Indian Ocean as a part of the ADSS-1 [Levchenko and Matsievskii, 2000; Zubko et al., 2003].

Construction of the bottom seismograph determines, to a large extent, the level of noise caused by the near-bottom currents, reliability of installation at the bottom and emersion, and usability. Installation of the modern broadband autonomous seismograph of the IO RAS is schematically illustrated in Fig. 2; the appearance of the seismograph is shown in Fig. 3.

The seismograph consists of a remote container of the seismic sensors 450 mm in diameter and an instrumental container 650 mm in diameter made of titanium and connected by a multicore cable with a length of 50 m. The total mass of the equipped seismograph is of about 80 kg. A bottom container holds a vertical and two

Fig. 3. Appearance of the instrumental container and seismic sensor block (uncovered) of the bottom seismograph of the IO RAS.

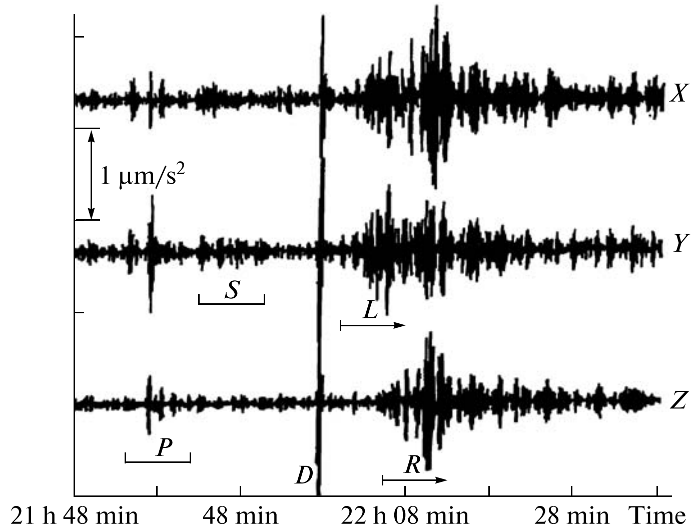

Fig. 4. Compressed record of the Himalaya earthquake (October 19, 1991, $M = 6.7$) obtained with the bottom seismograph of the IO RAS in the central part of the Atlantic Ocean at a distance of 9800 km from the epicenter; the characters denote P and S groups of the volumetric waves and the Love (L) and Rayleigh (R) waves.

horizontal electrochemical seismic sensors, a three-channel low-noise amplifier, low-pass filters, AD converters, economic microcontroller with a buffer memory device, and an orientation block.

The instrumental container holds a controlling microcomputer with a hard drive, a bottom part of the hydroacoustic communication channel, a ballast breaker, radio and flash beacon for searching for the emersed station, and a common power source. The instrumental container has positive floatation and is kept near the bottom by a ballast and a line with a length of about 3 m. The line is needed for prevention of suction of the container by soft bottom [Sutton et al., 1981; Solov'ev, 1985; Trehu, 1985b].

The seismograph is installed to the bottom to depths up to 5000 m in free fall by throwing overboard a providing vessel. The containers are spatially separated with the use of a special wing attached to the cable near the bottom container. Cohesion of the block of the seismic sensors with the bottom is improved by an external load. The station is lifted as follows. A hydroacoustic signal is transmitted from the vessel, a hydroacoustic antenna and a hydroacoustic block receive the signal, the ballast breaker operates, and the station emerges.

In general, the construction of the broadband bottom seismograph of the IO RAS is sufficiently reliable and usable for operation in the autonomous regime. At the same time, the instrumentation of the container of the seismic sensors represents a complete complex which can be connected to the communication and power supply cable for operation in the stationary regime.

SEISMIC SIGNAL RECORDING BY BOTTOM SEISMOGRAPHS

For twenty years of recording of the earthquakes and microseisms at the bottom of water areas within a wide frequency band (0.003–20 Hz), the researchers of the IO RAS have collected great experimental experience. Below, some examples are presented.

In October 1991, during the fifth trip of the scientific-and-research station Akademik Ioffe, bottom seismic recording was performed in the center of the Atlantic Ocean southward of the Azores. The seismograph was installed at a depth of 1660 m by about 10 km eastward of the axis of the rift valley of the Mid-Atlantic Ridge and about 23 km north-eastward of crossing the valley by the transform fault Oceanographer. A remote (9800 km) earthquake with the magnitude $M = 6.7$ was recorded which happened on October 19 in 21 h 23 min 17 s in The Himalayas. Figure 4 depicts a time-compressed three-component record of the earthquake. Earthquake duration was 10 s, but

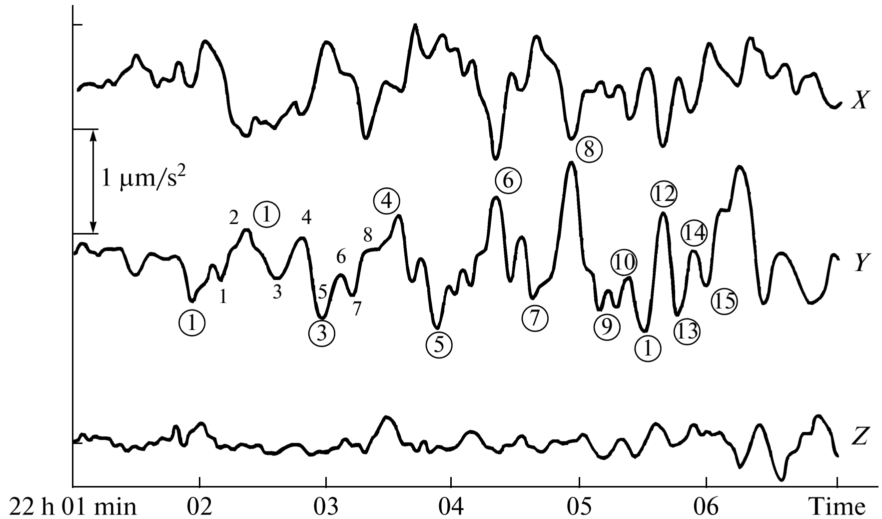

Fig. 5. Scanned record of the Love wave from the Himalaya earthquake (see Fig. 4); the numerals denote maxima of the first and second harmonics.

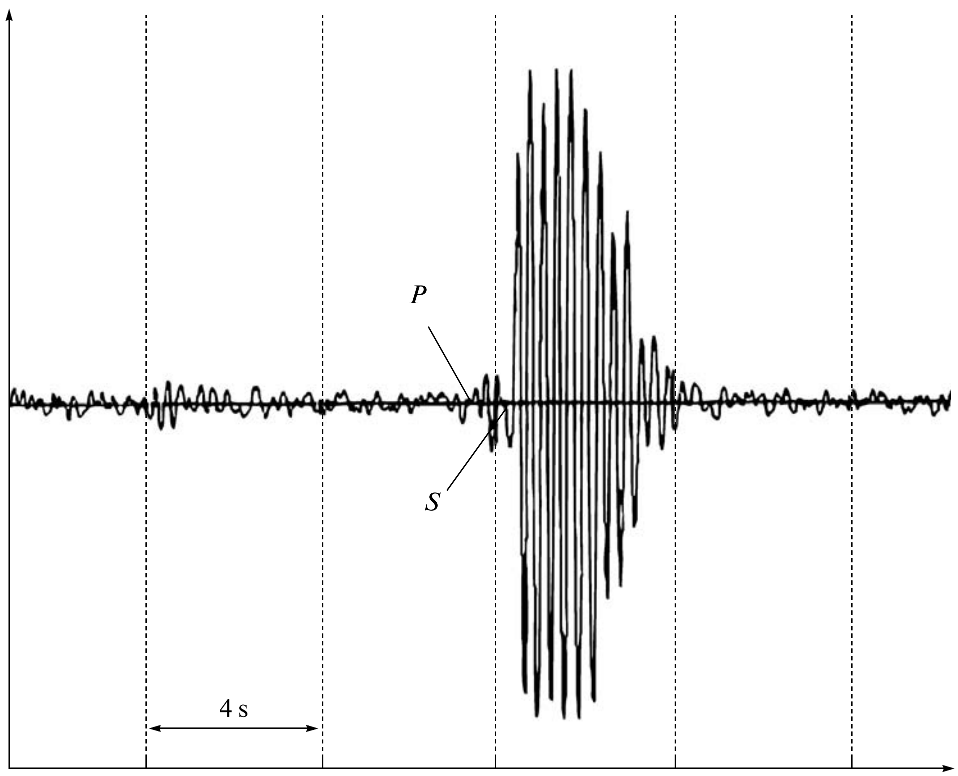

Fig. 6. Record of the local earthquake (August 20, 1999, $M = 2.5$) obtained with the bottom seismograph of the IO RAS in the region of the Caucasian continental slope of the Black Sea.

the signal was recorded for about two hours because of wave dispersion. A scanned record of the Love wave of this earthquake with the marked maxima of the first and second harmonics is shown in Fig. 5. The analysis of dispersion curves of the group velocities of these waves revealed waveguides at depths from 60 to 80 km and from 160 to 200 km which were previously unknown in this region [Levchenko et al., 1994].

In the period from 1999 to 20001, researchers of the IO RAS performed geological and geophysical investigations in the north-east part of the Black Sea continental slope in the regions of the constructed Russian-Turkish undersea gas line and oil-loading terminal near Novorossiisk. As a result of the bottom seismologic observations in August and September 1999 and September 2001, over 1200 seismic events were

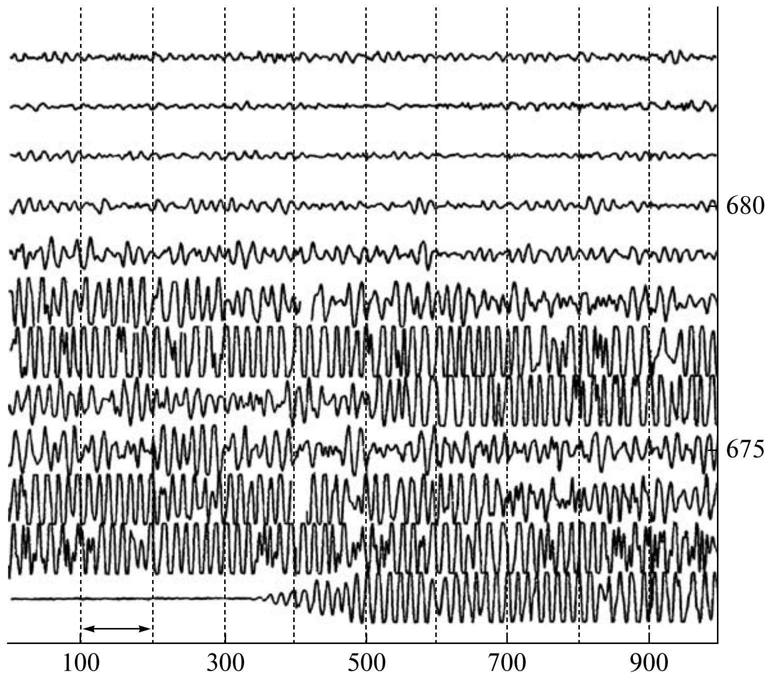

Fig. 7. Record of the long-term seismic event (hypothetically, from an underwater landslip, August 25, 1999, $M = 2$) obtained with the bottom seismograph in the region of the Caucasian continental slope of the Black Sea (the arrows point an interval of 2 s).

recorded. The overwhelming majority of them (90%) were local microearthquakes and shocks with a magnitude of less than 1 or 2 which were not recorded by shore seismic stations. A record of one of the local earthquakes with the magnitude $M = 2.5$ obtained by a bottom seismograph in this region is shown in Fig. 6.

Figure 7 demonstrates a record of a long local seismic event ($t > 200$ s) which has no features of the tectonic phenomena and may be caused by an submarine landslip. During the expedition, several tens of such long records (about 80–250 s) were recorded by only one seismograph. It should be noted that high seismicity and extraordinary steepness (sometimes up to 30 deg) of this region favor the descent of a critical mass of sediments from the upper part of the continental slope.

During the expedition in the Motovskii Bay of the Barents Sea in May 1992, microseisms were recorded by the digital bottom station installed at depths of 148 and 30 m in the latitude 69°34′195 N, the longitude 32°41′5 E and the latitude 69°37′9 N, the longitude 32°04′5 E, respectively. On 20 and 21 May, in the middle of the Motovskii Bay seiche oscillations of the water surface were recorded which are fairly a rare seismic phenomenon. The oscillations coincided in time with the high tide and were apparently caused by a tidal current directed to the East-open entry of the Motovskii Bay (tide height difference is 2.5 m and a period of about 12 h). Excitation of such oscillations is described in the literature. The tidal current causes the near-shore eddies, which excite the natural oscillations of the water area.

The period of the fundamental oscillations was presumably about 1000 s, which corresponds to the period of the main mode of the natural oscillations in the longitudinal direction of the Motovskii Bay (length of about 20 km). However, such frequencies are below the lower limit of the frequency range of the spectrometer (0.003 Hz). The oscillations lasted over 10 hours. The signals were recorded by three components. The comparative analysis of the records showed that in the horizontal component spectrum (Fig. 8) odd harmonics (0.003 and 0.005 Hz) predominate, while in the vertical component spectrum, even harmonics (0.002, 0.004, 0.006, and 0.008 Hz) predominate. The features of the spectra are attributed to the fact that the vertical centroid shifts twice in the period; i.e., the bottom-loading pressure frequency doubles. The frequency of the shore-loading pressure of the seiche waves in the horizontal direction coincides with the oscillation frequencies of these waves. The bottom shift velocity amplitude for the vertical component was higher than that for the horizontal component approximately by a factor of 4. The estimated maximum height of the seiche waves was about 0.6 m [Levchenko, 2002].

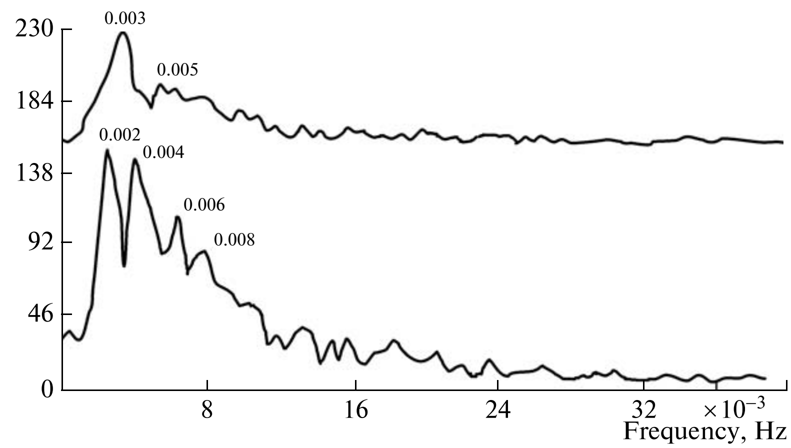

Fig. 8. Spectra of the vertical and horizontal components of the seismic signals caused by the seiche oscillations in the Motovskii Bay of the Barents Sea (recorded with the bottom seismograph of the IO RAS in May 1992). The vertical axis points dimensionless units. The graph of the *X* component spectrum is shifted by 160 units upwards. Even and odd harmonics of the basic oscillation with a frequency of 0.001 Hz are marked in Hz.

OPERATIVE COMMUNICATION WITH THE BOTTOM STATION

The challenge of the autonomous bottom stations is the operative communication with the shore or a providing vessel. This communication is necessary when a seismograph is intended, for example, for tsunami danger warning. Ordinary hydroacoustic communication operates at small distances, requires much energy, is subjected to reverberation noise, etc. It should be noted that recently developed communication systems with the use of complex coding and digital processing are much more noise-immune and have lower signal powers [Catipovic, 1997]. Also, in the newly developed techniques on the basis of floatable modules an express-signal is transmitted via a satellite or radio channel. However, these methods have not been used in the bottom seismographs.

In the current autonomous tsunami warning systems, surface retranslation radio buoys are used which are connected to the bottom station via a hydroacoustic channel (DART system, USA, and others). However, such a system has a number of shortcomings. The buoys of average dimensions (overwater and underwater heights are of 2.5 m and 1.8 m, respectively) are intensively affected by sea waves, which reduces the working life and reliability of the communication channels. Loss of such buoys is mainly resulted from buoy rope breaks due to fatigue loading. At the same time, there exist other constructions of long-term buoys that have been used in marine practice [Levin and Nosov, 2005].

In seventies and eighties of the last century, in the USA and USSR the so-called stabilized buoys were developed and used in research. Simplistically, such a buoy is an anchored vertical pipe with a length of 50 m submerged in water by its three fourths. Because of high stability and small windage, such a buoy has a small slope (units of degrees) even during strong storms and small vertical displacements (units of centimeters) relative to the average sea level. Due to a special anchoring system, the buoy does not rotate around the axis, which makes it possible to connect it to the bottom stations by cables. Such a buoy was installed in the South Branch of the IO RAS and used for ten years (1974–1984) [Lobkovskii et al., 2005].

There are long-term buoys with the use of an intermediate subsurface floatage (Froude spar buoy). Such an anchored floatage is located at a depth of 50–100 m where the surface waves cannot penetrate. Therefore, practically no dynamic loads affect the buoy rope. A stationary or submerging surface buoy is connected to the floatage. As the dimensions of the buoy are relatively small, in this case it does not considerably load a coupling element, which provides long (about 10 years) working life of the construction.

In 1995–1997, within the agreement with the EMERCOM of Russia, the researchers of the IO RAS developed a bottom observatory for registration of a number of parameters of near-bottom waters and studying possible precursors of the strong marine earthquakes. The observatory consisted of a surface retranslation buoy and a bottom measurement complex connected to a submerged buoy with power sources by a cable. Operation of the observatory had to be actively controlled. The observatory could operate either in the automatic regime with periodic data translation to the receiving point, in the request regime, or in the regime when periodicity and character of the measurements varied by instructions coming from the shore. The observatory was successfully tested in the Avachinsk Bay, Kamchatka [Gavrilov et al., 2000; Lobkovskii et al., 2005].

SEISMOLOGICAL MONITORING AND TSUNAMI RECORDING WITH THE BROADBAND AUTONOMOUS BOTTOM SEISMOGRAPHS

Currently, a number of methods of tsunami control and warning are used. One of the methods is based on the fact that seismic wave velocities are much higher than the tsunami velocity. Coordinates and a magnitude of a hypocenter of a marine earthquake are determined with land seismographs; then, using these data and a number of signs, the possibility of the tsunami occurrence is estimated. However, this method is extremely inexact, as at large distances (more than a source dimension) bottom deformation parameters cannot be determined; a considerable tsunami wave occurs only at vertical and incline motion of the bottom [Gutenberg, 1963; Savarenskii, 1972].

Another method is based on the use of deep-sea tsunami detectors installed far from the shore. These detectors measure pressure or water layer thickness and should have high relative sensibility. A tsunami wave 10 cm in height can multiply grow in the open ocean and be very dangerous. Therefore, the detectors installed to a depth of 3 km should have sensibility not worth than 3×10^{-5}, which can be provided by quartz pressure meters. Water layer thickness is measured with bottom echo-sounders of ultrahigh resolution.

One more difficulty is related to necessity of separation of a weak signal from tsunamis against the background of intense noise from long marine waves and atmospheric pressure variations. For example, in a DART system (USA), warning beep is given only in 30 min after the earthquake moment. It should be noted that if the earthquake epicenter location is a priori unknown, the detectors should be placed along the entire protected shore. When the detectors are installed autonomously, the same difficulties with their power supply and information transmission as those typical of the autonomous seismographs arise. The best developed systems of tsunami observation and warning which contain hundreds of land seismographs and a number of the deep-sea detectors are available in the USA (NOAA) and Japan (JAMSTEC) [Hanson et al., 2007; Levin and Nosov, 2005].

Tsunami can be principally recorded by satellite observation. However, providing the desired resolution in height and time of sequential scanning of the water surface of not worse than 5–10 min requires launching several tens or hundreds of altimeter satellites.

We propose the technique of long seismologic monitoring at the bottom of water areas and tsunami recording with the use of a system of the broadband autonomous bottom seismographs equipped with sensitive sensors and strong motion sensors, a channel of communication with a providing vessel, and retranslation buoys for transmission of express information. The formation of this system requires installation of several (about ten) long-term autonomous bottom seismographs at distances of about 100 km from each other in the regions where the strong earthquakes are expected. These stations will record seismic events in a wide frequency band directly in a zone of the expected earthquake.

In the design regime, the system will collect information on the seismic events preceding the strong earthquake. Since technical parameters of the bottom stations should be close to those of the land stations, the obtained information can be used collectively. This information is very valuable for fundamental study of seismic processes occurring in the regions of the highest seismicity, such as subduction zones, investigation of the ocean crust structure and superior mantle (down to depths 200–300 km), studying microseism generation and propagation in the ocean, ocean tomography, etc.

In the case of catastrophic earthquake (with a magnitude of about 8), the bottom stations with strong motion sensors record the elements of bottom motion and, using the retranslation buoys, transmit the express information via the satellite or radio communication channels. Such a system should provide reliable recording and classification of the tsunami earthquakes and danger warning within 5–10 min.

Let us consider the possibility of operation of the bottom seismograph in the area of the strongest marine earthquakes. As follows from the results of the special calculation, simulation, and experimental studies, the maximum vertical acceleration of the bottom in the case of catastrophic bottom earthquakes does not exceed 20 m/s^2. Such accelerations are normal for the bottom seismographs in strong casings protecting the devices from pressure and shocks of the bottom and a vessel hull. The electrochemical seismic sensors can bear shocks up to 30 m/s^2 and operates at any inclination; therefore, they do not need in a gimbal suspension, which requires some time for damping after overload.

The standard sensitive electrochemical seismic sensors have a limited dynamic range of about 120 dB. Therefore, recording of strong earthquakes requires special strong motion seismic sensors low-sensitive to special orientation, such as an A1638 detector developed at the VNIIFTRI. Also, strong motion electrochemical seismic sensors can be developed. Sensitivity of such detectors is proportional to the square of internal grid electrodes through which an electrolyte (inertial mass) moves upon sensor casing oscillations. In the sensitive sensors, this square equals to units of square centimeters. A decrease in the square will allow reduction of sensitivity to the required level.

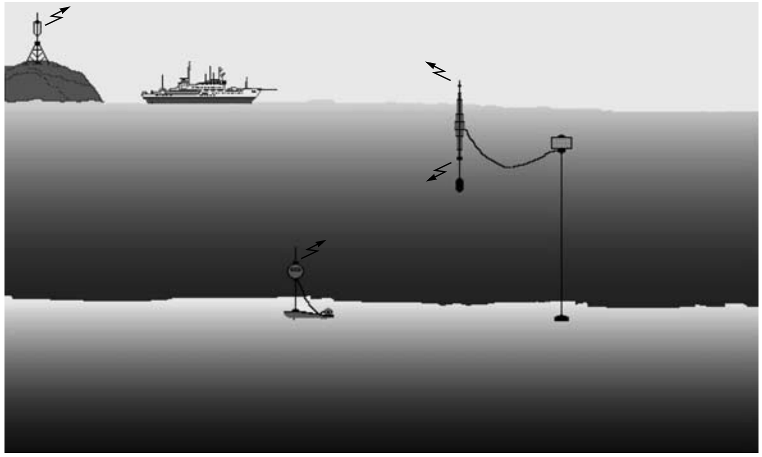

Fig. 9. Installation of the developed complex of the autonomous bottom seismograph with operative communication and the submerged and retranslation buoys.

Such a system of monitoring and warning will cost much lower (in tens of times) than the cable bottom seismologic systems. According to the preliminary estimates, an autonomous bottom seismic station for the proposed monitoring system at small-series production will cost not more than 3 million rubles. Below, we list the approximate characteristics of the bottom seismograph for the monitoring system.

For the sensitive seismic channels:

frequency band	0.01–20 Hz
dynamic range	120 dB
sensitivity threshold	10^{-8} m/s

For the strong motion channel:

dynamic range	3 g
sensitivity threshold	10^{-4} m/s^2
hydroacoustic communication distance	up to 10 km
seismograph installation depth	up to 5 km
seismograph weight (in air)	up to 100 kg
time of express signal formation and warning	up to 5 min
time of continuous operation at the bottom without change of power sources	3–6 months

Figure 9 presents a sketch of the developed autonomous bottom seismic station for long monitoring. The bottom seismograph including seismic sensors, a digital recorder, buffer memory, and control microprocessor is located at the bottom and connected to a submerged buoy by a hydroacoustic communication channel. The submerged buoy that contains a central control device and power sources is located at a depth of about 100 m beyond the zone of the action of the surface marine waves and wind currents. The buoy is kept submerged with the ballast which can be detached by an instruction. The retranslation radio buoy containing the vessel-provided communication channels with the shore, an exact time signal receiver, and an express information transmitter via a satellite channel is located at the water surface and connected to the submerged buoy by the cable.

The constriction of the submerged buoy and the ballast should provide substantial reduction of the effects of deep currents on displacement and rotation around the axis. During the design of the radio buoy and its communication elements, one should obtain stability against the marine waves along with underwater and overwater windage and high stiffness. In the normal regime, power supply and transmission of the control instructions and the recorded data between the elements of the station is implemented via the cables. In order to increase reliability in emergency cases, the bottom seismograph, the submerged buoy, and the radio buoy have to be equipped with reserve power sources and channels of the noise-immune hydroacoustic communication between the elements of the station and the providing vessel. The power sources are changed during temporary raising the submerged buoy by the providing vessel approximately twice in half a year.

CONCLUSIONS

1. The overwhelming majority of the earthquakes occur under the ocean and sea bottom; however, the stationary marine seismological network is practically absent. The land seismographs record signals from the remote marine earthquakes with substantial distortions; the signals from the weak earthquakes are not recorded at all. For this reason, the geotectonic processes occurring in the Earth's interior cannot be adequately estimated in their unity and variety. Also, the deep structure of the ocean crust and the superior mantle and the mechanisms of excitation of tsunamis and other seismic events are understudied. Short-term prediction of the strong marine earthquakes and tsu-

nami warning remain the urgent problems. Therefore, the formation of the integrated seismological network on land and at sea is extremely important.

2. Recording of the seismic signals at the bottom of water areas considerably differs from that on land. The main differences are the presence of the effects of a water layer and a water-flooded sediment layer, the interaction between the seismograph casings with the soft bottom, the excitation of noise by near-bottom currents. In addition, there are engineering problems. The bottom stations operate in the automatic regime; therefore, they must be highly reliable. The stations need in strong casings for protection from pressure at depth and shocks during installation. Also, it is difficult to provide long-term power supply of the autonomous instrumentation and transmission of the seismological information to the shore. A cardinal solution could be the use of the submarine cables; however, submarine cabling is extremely expensive, whereas reliability of the reused cables is low.

3. Because of the current absence of the stationary marine seismological network for solving the marine seismology problems, the autonomous bottom stations are mainly used. Their high mobility allows fast deploying of the station network practically in any World Ocean region of interest. The configuration of the polygon can be chosen according to the specific problems and instrumentation available. The cost of the ABSS is much lower than that of the cable stationary stations. Modern scientific and engineering achievements in marine instrument-making allow overcoming many difficulties of the development and use of the autonomous bottom seismographs. The modern electron elements of the measuring and computation technique and memory devices provide long-term operation of the autonomous instruments at the bottom without changing power sources. There exist the long-term buoys which provide stable communication with the autonomous station via radio or satellite channels. The aforesaid makes one conclude that the stationary marine seismological network whose metrological parameters would approach those of the land network should be formed on the basis of the long-term autonomous bottom seismographs.

The important advantage of the proposed approach is possibility to accomplish the works in the foreseeable future with reasonable expenses.

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