Investigation of long waves in the port of Kholmsk, Sakhalin Island

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Abstract. To increase the efficiency of the Tsunami Warning System (TWS) for the Sakhalin area new equipment was developed for transmission to the Tsunami Center of real-time information pertinent to the development of wave processes, and it was tested in the port of Kholmsk. The comparative spectral analysis of records received during a cyclone and in usual weather conditions has revealed an increase of energy fluctuations in a range of periods from 2 to 25 min, a range usually detected during a tsunami, and also the presence of two well-expressed maxima with periods of about 8 and 3 min.

There were digitized records of all visible tsunamis registered by mareograph in the port of Kholmsk. The tsunamis with sources in the Sea of Japan caused a significant increase of energy in a range of periods 5–25 min; at the same time waves coming from the Pacific Ocean displayed a lower-frequency area of the spectrum and, particularly, contained an evident maximum with a period of about 60 min. In the spectra of records of all tsunamis observed in this place there is a well-expressed maximum with a period of about 8 min. This peak most likely corresponds to the so-called Helmholtz mode of free oscillations, the nodal line of which lays near a bay entrance; the fluctuations on all defined areas of the port water occur in phase.

The numerical modeling of long-wave movements in Kholmsk bay has revealed the presence of a well-expressed mode of free oscillations with a period of about 93 s having two nodal lines on the defined area of port water. The peak observed during a cyclone with a period of about 3 min is caused, most probably, by this mode, and a doubling of the period can be caused by nonlinear effects in a stilling well pipe of mareograph or by peculiarities in the system of transforming the signal into digital code used for data transmission to the Tsunami Center.

1. Introduction

The existing Tsunami Warning System (TWS) for coastal communities of the Sakhalin area has a number of essential deficiencies. It is caused, first of all, by the absence in the Tsunami Center of operative information about wave process development. The available sea level observation stations are not adapted to address this problem since they are serviced by an observer once a day and there are no technical devices for wave height data transmission in real-time mode. Functioning only on the basis of seismological information, it is difficult for the TWS to determine when to issue an all-clear warning. At present two tidal gauges (given to TWS by U.S.A.) are being installed

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in the Kuril Islands for the purpose of collecting information about tsunami propagation.

To make the use of such information possible, the Sakhalin Tsunami Center, in conjunction with experts at the Special Research Bureau for Automation of Marine Research, Far Eastern Branch, Yuzhno-Sakhalinsk, undertook the installation in October 1999 of special recording equipment on a mareograph station, located in Kholmsk seaport (Fig. 1).

2. Organization of Data Collection in the Port of Kholmsk

In the Special Research Bureau for Automation of Marine Research a measuring complex for transmitting sea surface condition data in operative mode to the Sakhalin Regional Tsunami Center was developed. The complex consisted of tidal gauge, water, and air temperature sensors, connected to a personal computer in which was installed a board (L-205) with 16-channel analog-digital and single-channel digital-to-analog converters for producing a 12-digit code. A sea level sensor mounted on the axis of a standard mareograph transformed these fluctuations into an analog electrical signal, which was processed by the personal computer's analog-to-digital converter. For measurement of air and water temperature standard devices were used and data was recorded in 1-s increments. In the personal computer the raw data were transformed into physical values and averaged at 1-min time intervals.

Data is transmitted to the Yuzhno-Sakhalinsk Tsunami Center by an external modem through e-mail, and once every 10 min when potentially dangerous fluctuations of sea level are detected. A continuous visualization of measured and precalculated sea levels and seawater and atmospheric air temperatures is displayed on the computer screen. The results of temperature measurements played an auxiliary role and are not used by TWS; therefore they are not analyzed in this paper.

Constant monitoring of sea surface conditions at the research site on the Tsunami Center computer display allows the engineer on duty to judge the state of wave processes and to use this information for making appropriate decisions. However, it is necessary to study the characteristics of fluctuations caused by other potentially dangerous reasons (storm surge, seiche, harbor oscillation), to take into account their influence on energy increases in a range of tsunami periods that can cause difficulties in signal allocation. On the other hand, the decision concerning warning (or cancellation) should be based on the statistical characteristics of various tsunamis previously observed at this location. These questions are discussed in more detail below.

3. Anomalous Sea Level Fluctuations at Passage of a Cyclone

In examining sea level records in the port of Kholmsk, we found a number of cases of accelerated long-wave fluctuation amplitudes similar in structure

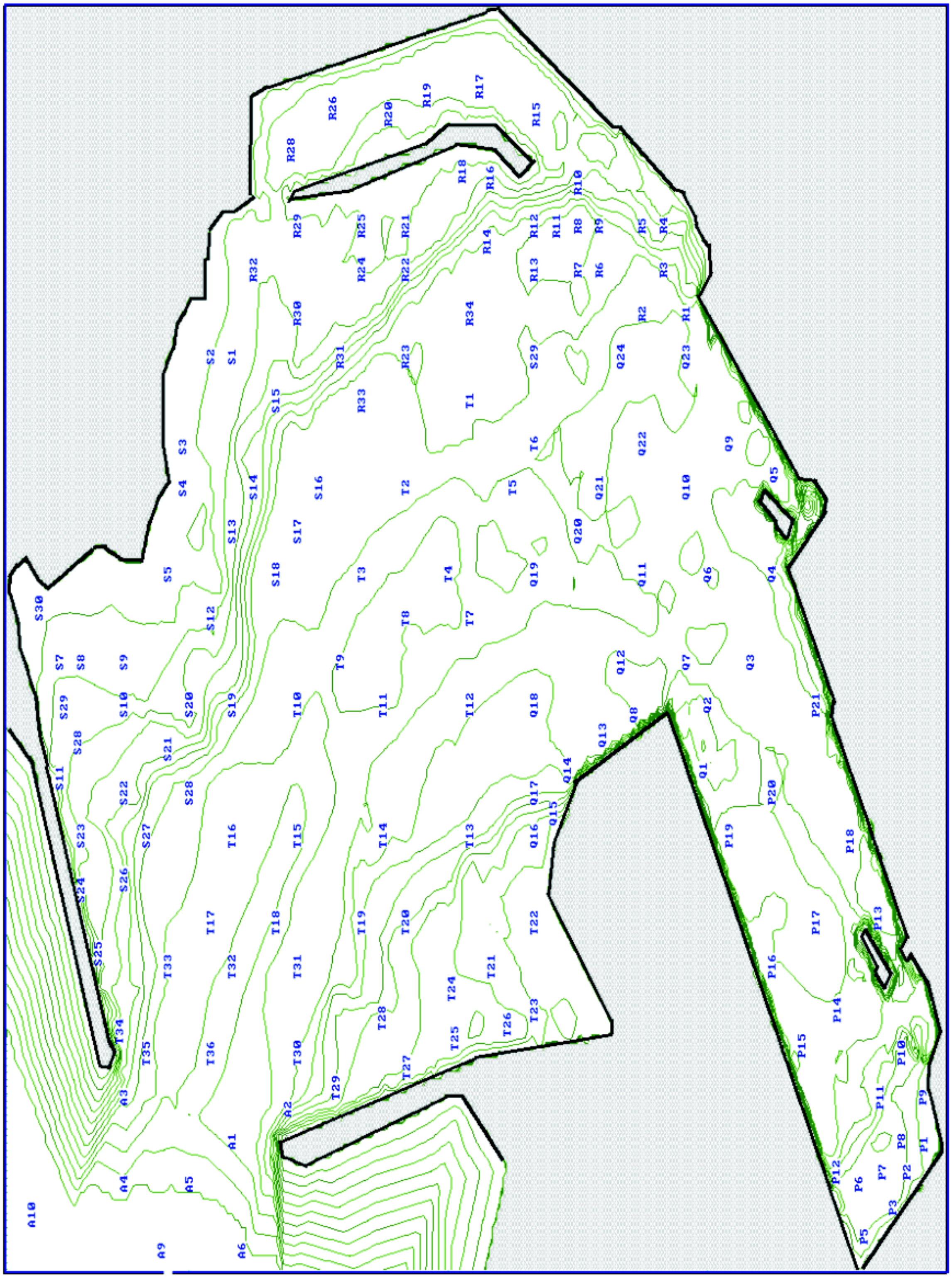

Figure 1: Kholmsk seaport.

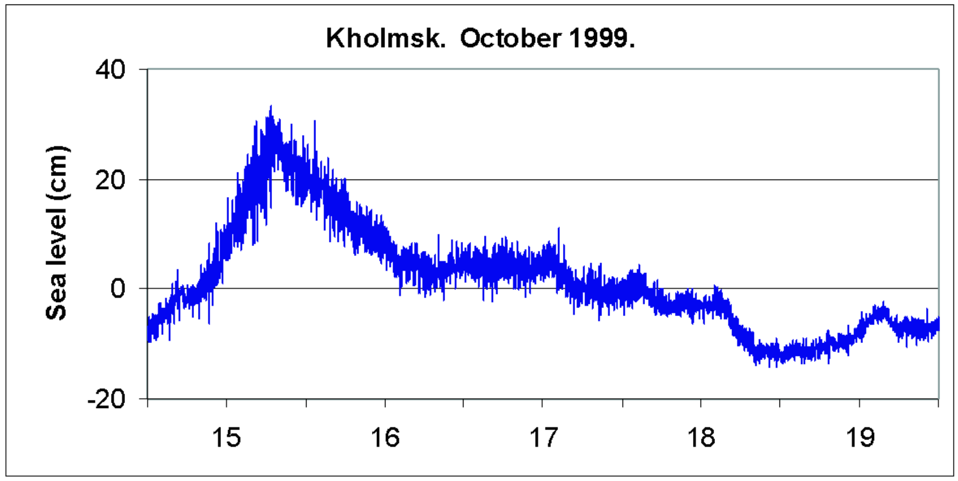

Figure 2: Storm surge, 16–17 October 1999.

to wave processes observed at the penetration into a bay of tsunami waves. These strengthenings of fluctuations were connected to the passage of cyclones, atmospheric fronts, etc., over the region. The example of similar fluctuations (a precalculated tide is subtracted from initial records) was associated with the passage over the researched region of a deep cyclone on 16–17 October 1999 (Fig. 2). At this time a storm surge of 35 to 40 sm (for more precise estimation it is necessary to analyze a series of greater duration), a characteristic height for this place, was observed.

The appropriate data records were selected for spectral analysis in order to research the wave structure of this phenomenon. For comparison, observation data from a quieter period (18–19 October) were used, when the influence of the cyclone was already insignificant.

Figure 3 shows the appropriate spectra calculated on the basis of the above-mentioned 2 days of data. The calculations were made with a time window of 6 hours, with displacement on half of the interval, so the number of degrees of freedom is equal to 30.

The spectra during a cyclone and in rather quiet weather conditions have a rather similar shape, though there is an order of magnitude difference in energy. The similarity of spectra is connected, mainly, with the presence in both cases of two well-expressed peaks with periods about 3 and 8 min.

The Kholmsk bay has a complex form and, therefore, the estimation of its free oscillations represents a difficult problem that can be investigated only by methods of numerical modeling. It is necessary to note that short-period fluctuations with a period of about 3 min are associated with the phenomenon of harbor oscillation, and the mooring of the Vanino-Kholmsk ferry-bridge is at this site; even weak harbor oscillation can cause negative consequences.

The period of about 8 min is most likely resonant for Kholmsk bay as a whole; thus the fluctuations in the port occur in phase.

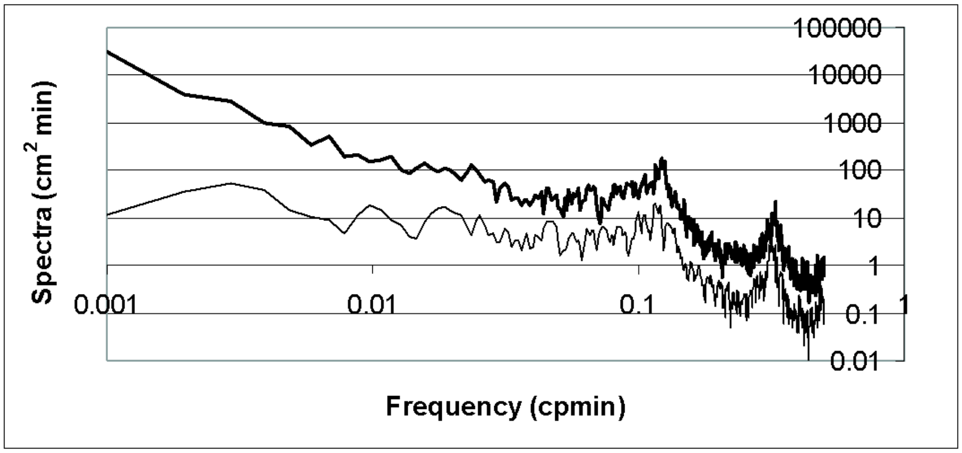

Figure 3: The spectra calculated on the basis of two-days pieces of recording.

4. Analysis of tsunami characteristics in the port of Kholmsk

As the observed anomalous fluctuations revealed great similarity to tsunami records in this place, appropriate mareograms were selected and digitized. In the port of Kholmsk there is a great number of records of various tsunamis—Kamchatka (November 1952), Chile (May 1960), Urup (October 1963), Niigata (July 1964), Moneron (September 1971), and Akita (May 1983) (Go *et al.*, 1984; Rabinovich *et al.*, 1992). Unfortunately, at one the of largest, the Okushiri tsunami of July 1993 in the Sea of Japan, the tidal station did not work, resulting in an incomplete selection of records.

Appropriate mareograms were digitized with a table digitizer with 1-min discretion and entered into the personal computer. Depending on the character of wave process development, the length of records received changed from 2 to 5 days (the longest fluctuations are fixed in 1960 and 1983).

For the spectral analysis data records with 2-day duration were selected; precalculated tide heights were subtracted from them (Fig. 4). The most dangerous for the given port was the Moneron tsunami, the positive deviations from an undisturbed level were up to 40 cm, and negative deviations were up to 20 cm. For the majority of other tsunamis the fluctuation amplitude was about twice less (about 30 cm). A noticeable essential distinction in character between a tsunami from a distant source (Kamchatka, Chilean) and one from a near source (Moneron, Akita), is the fact that for the latter the rather clear arrival of a wave and noticeable fading of fluctuation energy in time (unusual for tsunamis coming from the Pacific Ocean) are observed.

The spectral characteristics of tsunamis were calculated with the same parameters as with the passage of atmospheric phenomena, which allows us to compare the results.

On the spectra of all tsunami records, except the Chilean tsunami, as well as at the passage of cyclones and in quiet weather conditions, a powerful, highly noticeable peak on an ∼8–9-min period was found (Fig. 5). This

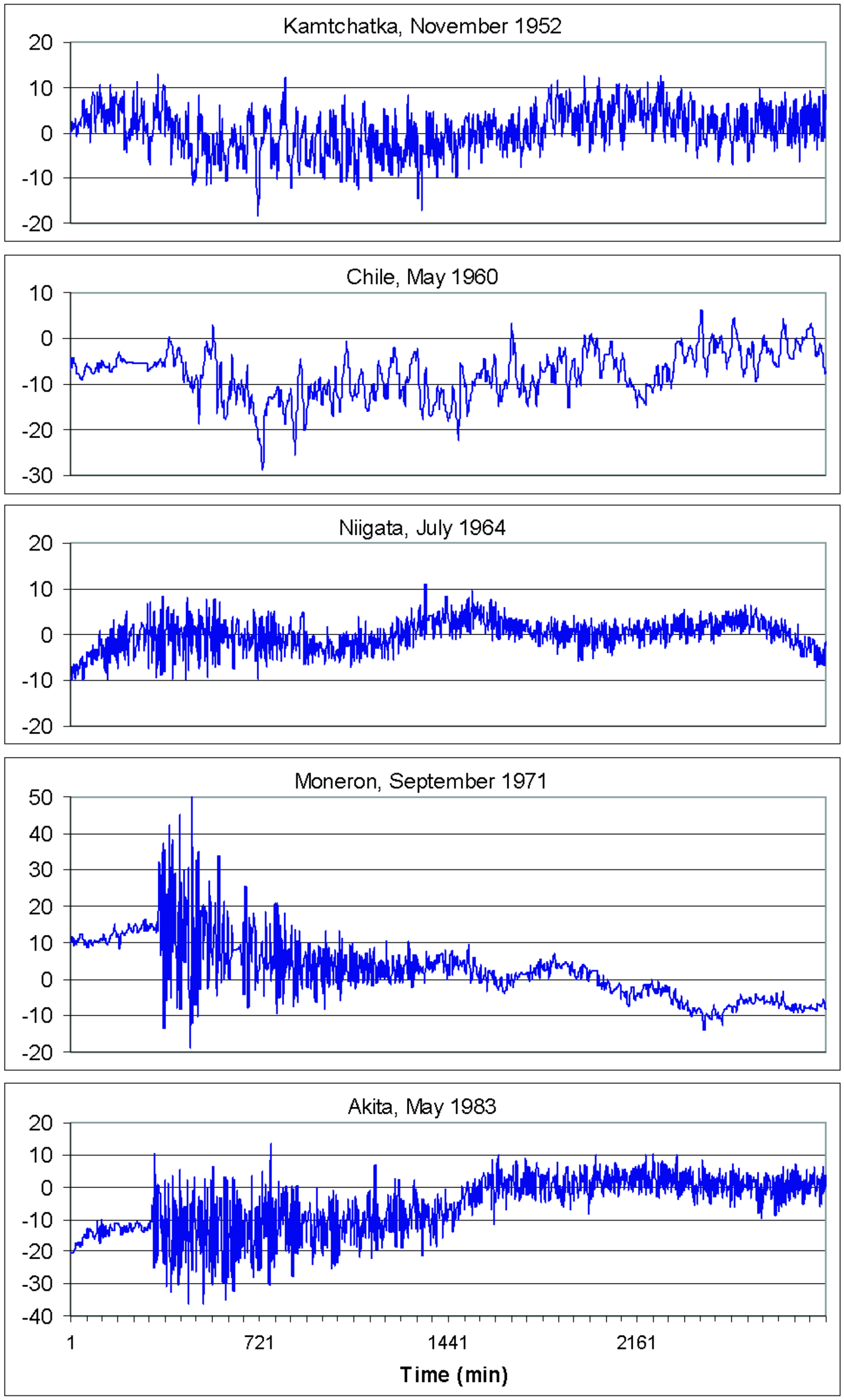

Figure 4: The records of tsunami in port of Kholmsk.

confirms the above-mentioned hypothesis that it corresponds to the basic period of free oscillations of Kholmsk bay. At a tsunami in a higher frequency area (periods less than 5 min) no noticeable increase of fluctuation energy level or presence of any peak are observed. In a lower frequency area a number of peaks is found, and their periods, as well as the bottom border of tsunami display for various cases, change in rather wide limits. The most low-frequency fluctuations are marked in the Chilean (May 1960) and Kamchatka tsunamis; in the spectra common peaks with periods of about 60 and 40 min are found. They are probably connected with the influence of topography on a line of tsunami propagation from the Pacific Ocean to the southwest coast of Sakhalin Island. In a spectrum of the Chilean tsunami also highly noticeable peaks with periods of about 45 min are also observed, which were detected in records of this tsunami at various stations, including the Chilean coast (Ivelskaya and Shevchenko, 2000); this indicates the probable connection of the appropriate fluctuations with processes in the source of the underwater earthquake.

It is interesting to note that all the tsunamis in the Sea of Japan had considerably higher frequency and that the basic energy of such tsunamis corresponds to periods less than 25 min (as mentioned above, the right border of a range of tsunami display periods was about 5 min).

At the passage of atmospheric phenomena the spectral density changes in sea level fluctuation have an essentially different character. For frequencies below the main peak with an ∼8-min period the increase of energy level is not very considerable, but in a higher frequency area a steady peak on an ∼3-min period is found (Fig. 3). As mentioned above, these fluctuations are most likely responsible for the phenomenon of harbor oscillation in the port of Kholmsk. Under the circumstances that these fluctuations did not appear at a tsunami occurrence but are connected to the passage of atmospheric phenomena, we assume [conveys for the benefit of opinion] that they are caused largely by the group structure of wind waves or surges that are usually caused by the passage of cyclones or typhoons.

It is necessary to note that at the end of the 1980s the port of Kholmsk underwent reconstruction; in particular, the entrance to the area of water under study was slightly extended and the bottom was deepened. As remarked in Rabinovich (1993), the widening of an entrance to a harbor usually results in a reduction of fluctuations and, accordingly, in a reduction of influence of harbor oscillation on the functioning of a port. The example under consideration is probably an exception to this rule.

The rather high-frequency fluctuations with an ∼3-min period in the port of Kholmsk is associated with bay resonant effects. It is surprising that they did not appear during a tsunami, which usually effectively raises resonant fluctuations in gulfs and bays, even taking into account the circumstances that a 3-min period is too short for mareogram digitizing of satisfactory quality. Probably, before the reconstruction the narrow entrance promoted to effective clearing of high-frequency fluctuations, in particular, at propagation of tsunami waves in the port defined area of water and also prevented from penetration of wind waves, surge and formed on shelf long-wave oscillations with the appropriate periods into the specified part of a bay.

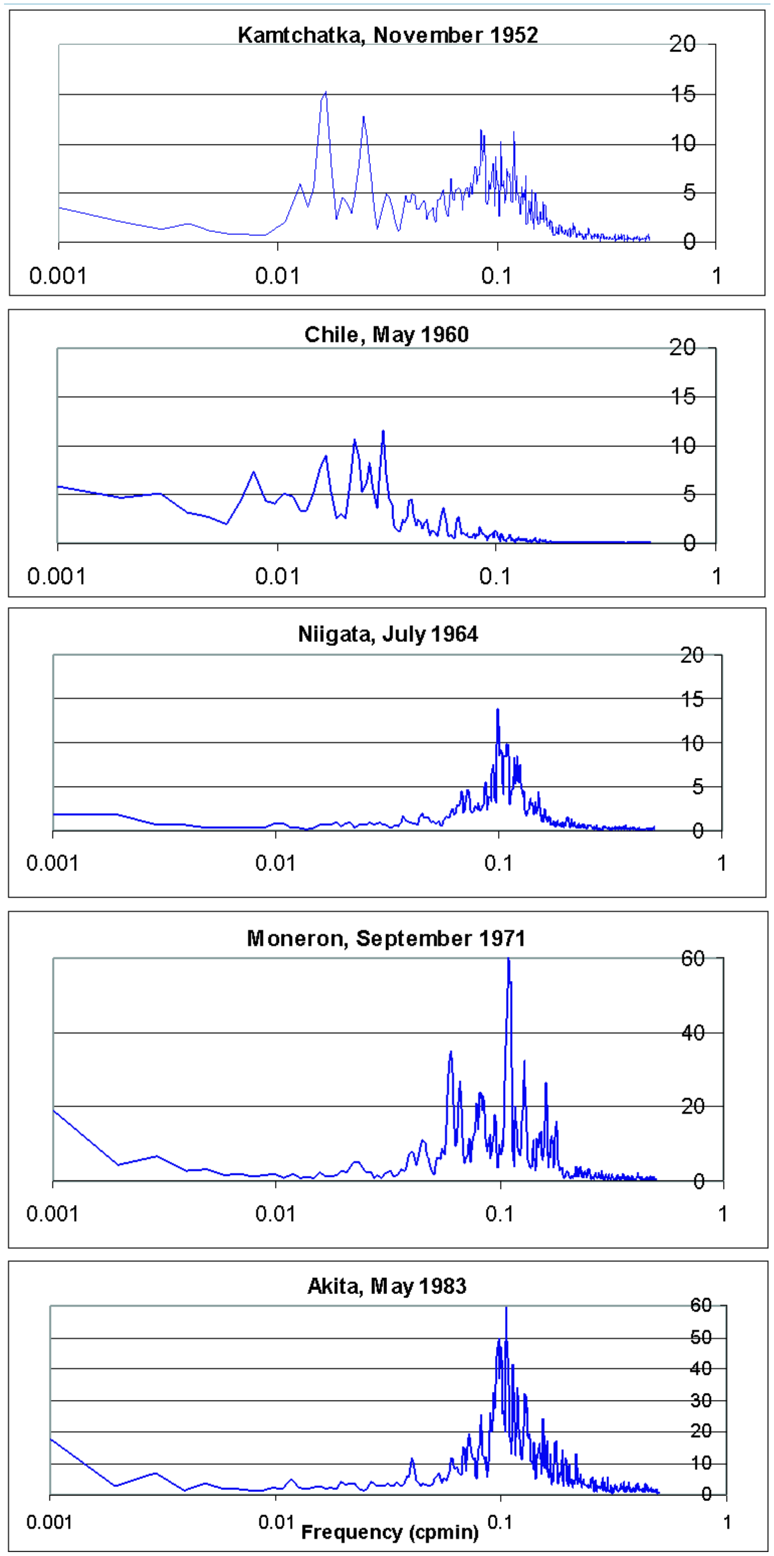

Figure 5: The spectra of records of tsunamis.

5. Numerical Modeling of Wave Processes in the Port of Kholmsk

For a more detailed study of fluctuation structure in Kholmsk bay numerical modeling of wave processes was carried out through a complex of programs, described in detail in (Poplavsky *et al.*, 1997). On an entrance into a bay an initial pulse was set as a positive deviation of the sine form with period 5 min, then the free long waves were propagated on the port area of water. In the investigated area 145 points were selected, in which fluctuations as a time number with 1-s discretion were fixed; the duration of calculated wavegrams was about 24 hours. The points selected were grouped on the port area of water regions and had the appropriate alphabetic specification (the point at the entrance was designated, for example, with the letter A, and in the most distant part of the bay with letter P, and so on). For each point the maximum amplitude of fluctuations observed in them is shown. The most intensive variations are observed in the region of moorings 8 and 9 from the internal part of the southern mole and also from the external part of the extended form island separating the internal harbor and the area between this island and the ferry mooring of the second turn. Some increase of intensity of wave process is marked also in the southern harbor at mooring 5.

The spectral characteristics were calculated by successive intervals with a 4-hour duration and for the analysis of free oscillations the first interval, extremely deformed by effects connected with characteristics of a source, was not involved.

The propagation time of a wave from the entrance into the bay up to its most distant part—mooring wall 5 in the southern harbor, not far from the mareograph location—was about 1.5 min. The same period is the basic resonant period for Kholmsk bay (calculations carried out for the bay bottom relief before the reconstruction of a port have shown that earlier this mode of free oscillations was displayed in a smaller degree). For a clearer representation of spatial structure of resonant fluctuations for the given period it was presented as a surface of meanings of gear function and shift of phases between point 9 at the bay entrance and all points on the port area of water.

The amplitude gear function for a period of 93 s points to areas of amplification of fluctuations: the internal part of the southern mole and mooring 9, the shallow-water zone from inside of the nothern mole, the area between the internal harbor and the ferry mooring of the second turn. Amplification of fluctuations near the island, separating the internal harbor, and also near moorings 5 and 8, is connected with the display of the second mode with a period of $\sim$55 s.

The surface of a phase of the first mode of fluctuations contains two nodal lines, in which there is an abrupt change of given parameter on size, equal to π. The position of nodal lines reflects the complex character of the spatial structure of free oscillations that is caused by the character of changes of bottom relief and coastal line in the port of Kholmsk—there are two lines: one crosses the bay on a line at mooring 8, the southern end of the island separating the internal harbor; the second crosses the southern harbor on a line between moorings 6 and 7 from one side and the ferry mooring of the first-order mooring from another side.

The presence of a nodal in the area of the ferry mooring means that significant horizontal speeds of water movement can be observed here that are associated with the phenomenon of harbor oscillation (Strekalov and Duginov, 1979; Rabinovich, 1993).

More low-frequency free oscillations were not discovered by numerical modeling. For the display of a so-called zero mode of resonant fluctuations (Helmholtz mode), the nodal line of which is in the area of the bay entrance, more extensive space in an external part (Rabinovich and Levyant, 1992; Rabinovich, 1993) is generally needed. Since in our case sufficient external space was not available, it is no wonder that this mode of calculated wavegram spectra was not discovered. Most likely, an 8-min period appearing during a tsunami as well as during stormy weather conditions corresponds to this mode.

It is more difficult to understand why fluctuations with an ∼3-min period were not shown by numerical modeling, which were found in spectra of records received through the device described above mounted to a mareograph in autumn 1999. Most likely, this peak actually corresponds to resonant fluctuations with an ∼1.5-min period and doubling of the period has occurred as a result of nonlinear effects at high frequencies filtration in the stilling well pipe of the mareograph. It is also probable that a similar influence of the auxiliary device itself, the choice of a 1-min data averaging period, was unsuccessful. The resulting problem requires additional research, as the distortions of signal structure in TWS are extremely undesirable.

Finally, to be convinced that there were not fluctuations with a 3-min period in the port of Kholmsk, we processed records received through a string wavegraph that was installed near the mareograph in January 2000. The measurements were made with a discretion of 0.25 s. The spectral characteristics of wave activity were calculated (observation data received during a storm on 7 January), and besides a powerful peak on periods of 5–7 s, a noticeable peak on a 93-s period appropriate to the resonant period of the first mode is also found. On the spectrum there are also two less noticeable peaks with periods 64 and 55 s, and the last corresponds to a resonant period of the second mode discovered at numerical calculations. Hence, good correspondence between results of numerical modeling and real wave processes is observed, and also, it is probably possible to make a conclusion that the free oscillations are effectively generated by wave activity. Most likely, the fact that after reconstruction of the port the significance of fluctuations of the first style has increased was displayed on the spectra of records received in the port of Kholmsk in autumn 1999, as a noticeable peak with a period of 3 min.

It will be possible to give a more exact answer to this question through a special experiment with repeated installation of a wavegraph and the temporary setting of the registration system in the stilling well to a 1-s discretion, which is planned for autumn 2000.

6. Conclusions

Besides improving technical details of transmitting information about long-wave processes in a measurement site, and debugging software for its reception and visualization on the monitor at the Tsunami Center, on the basis of collected data some research problems connected with the determination of the frequency structure of dangerous sea phenomena of various types were solved. It is shown that all types of long-wave processes in the port of Kholmsk have common features, connected, first of all, with the display of the basic mode of free oscillations with an ∼8-min period, but that it was not possible to confirm this by numerical experiments because of the insufficient size of an external part of defined water area.

Certain distinctions were discovered: at anomalous fluctuations of sea level of meteorological origin in the spectra of records there was a highly noticeable peak with an ∼3-min period that is probably caused by resonant effects of the first mode of free oscillations with an ∼1.5-min period. The doubling of the period is most likely connected with nonlinear effects in the stilling well pipe or with peculiarities of the device which transforms the fluctuations of a pointer into a digital code for transmitting to the Tsunami Center. These fluctuations are not displayed during a tsunami; probably, they are caused by the structure of wind waves or surge and, most likely, are responsible for the phenomenon of harbor oscillation, complicating the functioning of the port and, in particular, of the Vanino-Kholmsk ferry-bridge.

As a result of the spectral analysis of digitized mareograms of tsunamis recorded at the mareograph station (besides a common peak on periods of 8–9 min) some important distinctions of their characteristics are revealed. Therefore, the basic range of periods in which a tsunami with sources in the Sea of Japan occurs, is equal to 5–25 min. At the same time, distant tsunamis caused by strong earthquakes in the Pacific Ocean have caused an essential increase of energy in a range of periods of 30–60 min.

The specified features of dangerous sea phenomena on the water in the port can be considered and used for increasing the safety of operation.

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