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Concept for Developing a Seismologic Observation System for Tsunami Warning in the Russian Far East

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Abstract—The initial information and requirements for developing a seismologic observation system and data-processing and transfer tools for a tsunami warning system and its functions and tasks are considered. The structure of the seismologic observation system for the tsunami warning service (TWS) in the Russian Far East is proposed. A study of general technical and methodological problems is carried out to increase the efficiency for urgent tsunami prediction from continuous seismic monitoring data of territories of the Russian Far East and the world. Special attention is paid to the problem of tsunami prediction from seismologic data on strong earthquakes in near zone of a protected territory (up to 200 km).

Keywords: seismology, tsunami, seismologic observation system, operative tsunami prediction, near zone.

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INTRODUCTION

Tsunamis are dangerous natural phenomena that can lead to mass deaths, destruction of populations, and economic damage. In the 20th century alone, powerful tsunamis repeatedly struck Russia's Pacific coast (1923, 1952, 1959, 1969, and 1994). The main factor causing tsunami waves (approximately 85%) are underwater earthquakes. Historic and geological data reliably substantiate a high level of tsunami and earthquake danger for the Russian Far East; it is certain that these natural hazards will be repeated here systematically in the future [Solov'ev, 1972; Levin, 2005].

The Tsunami Warning Service (TWS) was established in the Russian Far East after the destructive 1952 tsunami struck the Kamchatka Peninsula and Kurile Islands. Using the data of three-component recording of seismic signals, it is possible to find epicenter coordinates and magnitude, i.e., to determine the origin and energy of the earthquake. Estimation of the probability of a tsunami from these parameters is the essence of the magnitude–geographic criterion, which continues to be the basis of the TWS' work [Savarenskii, 1956; Poplavskii et al., 1997].

So that a tsunami warning will be timely, the location of the epicenter and earthquake power should be determined with minimal delay after its onset. For this TWS seismic stations were equipped with specially designed seismic apparatus, which was their basic equipment [Kirnos and Rykov, 1961]. These are standard mechanical seismographs with small amplification and UBOPE (*Ustroistvo dlya Bystrogo OPredeleniya Epicentra*; Device for Rapid Determination of Epicenter), specially designed for operational work with amplification from 1 to 30. The range of recorded periods is $T = 2$ to 4 s at a level of 0.9 [Apparatura..., 1974]. These mechanical installations, intended for recording strong earthquakes at epicentral distances of 150 to 2000 km in a narrow range of periods of 0.2–4.0 s, became obsolete long ago, but are still used in the TWS at the Severo-Kuril'sk and Petropavlovsk-Kamchatskii seismic stations. At the Yuzhno-Sakhalinsk seismic station, they were removed in the late 1980s.

In the 1960s, standard Kirnos system devices were additionally installed at the stations; the natural oscillation period of pendulums was $T_S = 12$ s [Apparatura..., 1974]. Due to the small dynamic recording range of these devices, they can be used only for more distant or relatively weak nearby earthquakes. In the Kirnos devices, the seismic signals were recorded on photographic paper, which made it impossible to use them for operationally estimating the azimuth of the epicenter.

In the 1970s, seismographs with recording on thermal paper SKD-UP-SPR ($T = 20$ s; $V = 1000$, 200, 50, and 10) [Apparatura..., 1974] were installed at the stations. Their use for recording strong nearby earthquakes was limited by magnitudes of $M = 6.0$–6.5 due to the small dynamic range of the SKD pendulums. Then visible recording by the SKD–UP-SPR channel was introduced, and long-period DS-BP seismographs [Apparatura..., 1974] were installed.

September 23, 1980 saw the adoption of the USSR Council of Ministers Decree (No. 821) "On Measures for Further Improving and Organizing Timely Warning of the Population in Far East Coastal Areas about Sea Waves Caused by Underwater Earthquakes (Tsunami)." This council decree led to the establishment of the Unified Automated System "Tsunami" (UAST) for observing the occurrence and propagation of tsunamis in the Far East in 1985–1990. During the implementation of the mentioned decree in the early 1980s, the UAST's structure was developed, including seismic and hydrophysical subsystems, a communication subsystem, and several information collection and processing centers. In the course of the studies, the methods and algorithms for automated tsunami prediction were developed [Poplavskii et al., 1988]. In the late 1980s and 1990s, the tsunami problem became of secondary importance in Russia for several objective reasons, and these projects were not completed.

Increased world interest in the tsunami warning problem at the present stage is due to the very strong Sumatra–Andaman earthquake of December 26, 2004, which triggered a catastrophic tsunami that caused more than 200000 deaths and significant economic damage. In accordance with an order from the RF President, work on TWS development was included in the Federal Target Program "Decreasing Risks and Mitigating the Consequences of Extreme Situations of Natural and Technogenic Character in the Russian Federation up to 2010." In 2006 to 2007, in the framework of state contracts for implementing the R&D project "Development of a Network for Seismologic Observations and Data Processing and Transfer Tools for Tsunami Warning," Geophysical Service, Kamchatka Division, Russian Academy of Sciences, developed the concept for a seismologic observation system for the TWS (SO TWS) in the Russian Far East. The work was carried out in the framework of measure 18 of the Federal Target Program "Decrease of risks and mitigation of consequences of extreme situations of natural and anthropogenic character in the Russian Federation up to 2010"; the state customer was the Federal Service for Hydrometeorology and Environmental Protection (Rosgidromet) and the executor was the Geophysical Service of the RAS (GS RAS). Specialists from the leading institutes of the RAS participated in this work (Institute of Marine Geology and Geophysics, FEB RAS; Institute of Volcanology and Seismology, FEB RAS; Instituteof Physics of the Earth, RAS; Institute of Oceanology, RAS; Institute of Computational Mathematics and Mathematical Geophysics, Siberian Branch, RAS).

Today, the TWS in the Russian Far East is a functional subsystem of the Joint State System for Prediction and Liquidation of Emergencies (JSS PLE TSUNAMI), which is an interagency organizational structure. Seismologic observations are carried out by the GS RAS, and sea level monitoring is done by Rosgidromet.

The main goal of developing the system of seismological observations and data processing and transfer tools for the TWS is a step-by-step decrease in natural disaster risks caused by tsunamis; maximal reduction of death and material damage risks; improvement in protecting critically important objects from tsunami danger in order to provide safe human activity and sustainable development of the Russian Far East region.

In order to implement this goal, a substantial increase in the effectiveness and reliability of detecting and recognizing tsunamigenic earthquakes must be achieved by means of (1) technical reequipment of the seismologic observation network, (2) development of new approaches to data analysis and their software implementation, (3) creation of informational and scientific-methodical support for decision making on the possibility of tsunamis.

INITIAL DATA AND REQUIREMENTS RELATING TO PRINCIPLES OF ORGANIZATION OF THE SO TWS

We shall list the initial data, requirements, and preconditions for developing the seismologic observation network, data processing, and transfer tools for the purpose of increasing the effectiveness and reliability of tsunami warning.

Possibility of seismic method in principle. Reliable early warning of tsunamis is made possible by the substantial difference in the propagation velocity of seismic waves in the Earth's crust (4–7 km/s) and tsunami waves in the ocean (0.1–0.2 km/s). Thanks to this, a certain time period is created, in most cases very short, between recording of seismic waves from an underwater earthquake and tsunami wave arrival at the nearest coastline.

Locality and time resource. The overwhelming majority of historically observed tsunami overwashes (99.5% of their total number and 95% of all destructive tsunamis) have taken place at distances of up to 200 km, more rarely to 1000 km, from the earthquake epicentral zone (local and regional tsunamis). All deaths and the greatest damage are observed during the first hour of wave propagation [Gusyakov et al., 2006].

In the physical and geographical conditions of the most dangerous region in the Far East, namely, the Kurile–Kamchatka region, the travel time of the tsunami head wave to the nearest coastal areas does not exceed 15–20 min if the earthquake occurs in the limits of the continental slope. Therefore, the tsunami warning signal must be generated in a period no greater than 5–10 min. This imposes quite severe requirements on the configuration of the observation system, communication system, and structure of technical and software tools of the processing system.

Observation network and its problems. Today, the Tsunami Service in the Russian Far East is comprised of the Petropavlovsk-Kamchatskii, Yuzhno-Sakhalinsk, and Severokuril'sk seismic stations, which are part of the GS RAS observation system.

The main shortcomings of existing SO TWS systems in the Russian Far East are as follows:

– the equipment of seismic stations for TWS purposes is obsolete and hinders the integration of sensors in the information system, and the analog sensors themselves do not corresponded to modern demands;

– the technology and methods of decision making on tsunamis need to be revised (this has essentially not been done since 1959);

– seismogram processing is done manually or is in part automated without allowance for TWS requirements;

– the precision of estimating earthquake coordinates and magnitude in the operational regime is low;

– a decision on the risk of a tsunami occurring after a very recent earthquake is made by each seismic station independently, with no combined analysis.

Foreign experience. Beyond Russia, in several of the tsunami warning systems ,these shortcomings have mostly been overcome. The basic approaches in making decisions on the possibility of a tsunami in the TWS of Japan, the United States, and France [Sokolowski et al., 1990; TREMORS, 1995; Tatehata, 1997; ITSU Master Plan, 1999; Koya et al., 2006] are as follows:

– seismic stations in the TWS are usually equipped with broadband digital seismometric channels and communication tools for data transfer in real time;

– estimates of basic earthquake parameters are made in the automatic mode for a group or network of stations and are confirmed by an operator;

– a decision on the possibility of a tsunami is generally made by an operator with allowance for operational analysis results and automatically generated recommendations;

– an iterative method of data analysis and decision making during data accumulation at each seismic station and in each data accumulation and processing center of the seismic station network;

– wide use of results of preliminary modeling of tsunamigenic earthquake sources.

Digital sensors and digital data analysis tools. Modern seismic sensors, combined with progressive digital technologies for data analysis and processing, make it possible to record seismic waves in a wide frequency range with high resolution and dynamic range. Modern computer hadware and the software developed for data processing substantially facilitates the problem of comprehensive and precise analysis of seismograms. Analysis of digital seismic records can be done with high effectiveness, with small delay from real time, in a completely automated mode, which may lead to a radical increase in the reliability and validity of operational tsunami prognosis from seismic data.

Multilevel structure. The seismologic observation system should have a hierarchical structure, in which low level components can solve monitoring, prognosis, and tsunami warning tasks in incomplete volume, but independently of the external communication lines. In many cases, low level components alone located close to the earthquake source can provide warning with an acceptable level of timeliness.

Warning decentralization. A necessary condition for timely provision of tsunami warning signals to the populace is direct output of the alerting signal to the possible tsunami warning system at the local level and interaction with the TWS subdivisions of Rosgidromet and EMERCOM (Ministry of the Russian Federation for Civil Defense, Emergencies, and Elimination of Consequences of Natural Disasters).

Elaboration of methodical principles. With regard to methods and algorithms, the existing TWS system is based on a system of premises that was quite adequate in the 1950s–1970s, but should be revised now.

1. The earthquake source was assumed to be punctual or practically local. In fact, the source of the 1952 Kamchatka earthquake was 500 km long, and the source of the Sumatran earthquake in 2004 extended over 1300 km. In such cases, the definition of the epicenter in the conventional sense can be misleading: a distance of 1500 km from the epicenter does not guarantee either small tsunami amplitudes or sufficient time for analysis of the situation. When making decisions, the TWS must take this factor into account. Ideally, the position of a prolonged source should be operatively determined, but there are no effective approaches to this problem yet.

2. The source process duration was assumed to be relatively small, not exceeding 20–40 s. In these conditions we can expect that *S* waves are usually recorded at regional distances with an acceptable signal-to-noise ratio; recording can be considered complete and processing of data for the subject earthquake can be started about 60 to 90 s after the arrival of the first seismic wave. As is now reliably known from the experience of the 2004 Sumatran earthquake, source duration of strong tsunamigenic earthquakes can reach 9 min. And this is not an anomaly: the source process duration for earthquakes such as the 1960 Chilean and 1964 Alaskan quakes reached, and probably exceeded, 4 to 6 min. In this situation the following problems arise:

– *S* wave arrival at regional distances overlies the intensive *P* waves from the still growing source, and detection of this arrival becomes a hopeless task. This means that for the strongest and most dangerous earthquakes, the position of the epicenter and magnitude cannot be reliably determined by a single station on the basis of the usual method for distance estimation by difference in travel times of *S* and *P* waves, and new approaches are needed, since evaluation of the magnitude is not possible without evaluation of the distance to the source;

– even in the limits of the presently adopted processing time resource of 10 min, reliable earthquake magnitude determination becomes impossible in principle, since the seismic waves from the source as a whole cannot reach the stations, so their future amplitude on the record is unknown. It is also highly desirable to shorten the processing time. Therefore, the TWS should in principle be freed from the task of operational magnitude estimation in the usual sense, and in place of this the current lower estimate of the magnitude should be continuously obtained and refined. In other words, at each moment of time after detection of a strong earthquake, the value of the parameter "temporal estimate of magnitude from the bottom" (TEMB) generated at this moment must be known. The sense of this parameter is that according to data at the present moment, the magnitude of the earthquake is no less than the TEMB, but it may become even larger. For the tasks of estimating tsunamigenicity, this modification of the processing task is quite acceptable.

3. It was believed that the tsunamigenicity of an earthquake is sufficiently well characterized by the magnitude, which is determined from surface waves with a period of 10–20 s. It has now become clear that there are cases when the source process proceeds relatively slowly, with a duration 100 s or more, and weakly excites waves with these periods. However, potential tsunami generation by this source process is high. This problem can be solved in principle by passing to estimates of earthquake energy at relatively long wave periods (50–100 s or more), and the "mantle wave magnitude" can be used for this purpose as well as its analogs. It can be supposed that the use of broadband digital equipment will create preconditions for solving this problem.

4. It was believed that the first *P* wave arrivals from tsunamigenic earthquakes always take place on the background of low seismic noise. This is often actually the case, but it also turns out that a tsunamigenic earthquake is preceded by powerful foreshocks with an advance of several tens of seconds, which makes *P* wave arrival detection very difficult (and *S* wave detection even more so). A possible partial solution is the use of small groups of devices and processing by group methods.

FUNCTIONS AND TASKS OF SO TWS

The primary purpose of the seismic observation system in the TWS (SO TWS) is to evaluate the possibility of tsunami wave generation by a strong earthquake on the basis of processing the kinematic and dynamic characteristics of seismic signals. The main problem is timely generation of a warning signal related to the possibility of a tsunami wave from earthquakes in the near zone (to 200 km from the earthquake source to the coast region or a population protected by the TWS).

A seismic observation network in the Far East for the TWS, equipped with adequate tools and having modern methods and algorithms for data processing and transfer, must perform the following basic functions.

1. Scientific-technical and informational functions:

– earthquake detection and recording in a 24-hour continuous regime in the zone of TWS responsibility in the Far East, namely, under the bottom of the Pacific Ocean, including the Sea of Japan, Sea of Okhotsk, Bering Sea, and the adjacent land mass;

– processing of seismic signals in an automatic and automated mode for fast estimation of the parameters of strong ($M > 6.0$) earthquakes in the zone of responsibility for the cases of a single station, a local group of stations, and a network of stations;

– decision making on the possibility of a tsunami by a single station, by a local group of stations, and by a network of stations;

– observation data exchange with Russian and international seismologic centers and tsunami warning centers;

– collection, accumulation, and systematization of seismologic observation data, generalization, and analysis of recordings of tsunamigenic earthquakes for the purposes of developing scientific-methodical and informational support for the TWS.

2. Administrative functions:

– transfer of results of seismologic data processing by the EMERCOM and Rosgidromet services on local, regional, and federal levels;

– transfer of tsunami warning signals on local, regional, and federal levels by the alerting schemes of the government, EMERCOM, and Rosgidromet services.

In order to solve the foregoing problems, the seismologic observation network and the tools for data processing and transfer for the TWS should evolve in the following directions:

– increase in the efficiency of operative tsunami prognosis using seismologic data in the Russian Far East (main task);

– continuous seismic monitoring of the territory of the Russian Far East and of the world;

– scientific and research studies for creating an informational and methodical basis for developing the seismologic observation system, tools for data processing, and transfer for TAS for the purpose of improving the effectiveness and reliability of tsunamigenic earthquake detection and recognition.

STRUCTURE OF THE SEISMOLOGIC OBSERVATION NETWORK

The seismologic observation network for the TWS must include (Fig. 1) seismic stations, a communication system for data transfer, information and processing centers (IPCs) of the seismic station network, and system devices for warning of the possibility of a tsunami.

Seismic stations

The basis of the seismologic observation system for the TWS are seismic stations that are created specifically for the purpose of detecting earthquakes, estimating their tsunamigenicity, and decision making about the possibility of a tsunami.

The specialized seismic stations of the TWS are subject to very high demands on their continuity of operation (hot reserving, duplication of main equipment elements), quality and reliability of initial seismic data and results of their processing (quality and reliability of seismic signal sensors and their adequate installation), staff qualification, and immunity to strong seismic actions.

In addition to the data from specialized seismic stations of the TWS, the real-time data available from the stations of existing regional and local networks for seismological observations (NSO) of the GS RAS and/or results of their processing can and should be used in solving the problem of operative tsunami prediction.

All the specialized seismic stations of the TWS should be equipped with

– standardized broadband seismic signal sensors;

– standardized equipment, methods, algorithms, and software for digital recording and processing of seismic data in automatic and automated modes:

– communication devices for transmission of initial seismic data and results of their processing to regional information-processing centers;

– local system devices for alerting the population of the possibility of a tsunami;

– uninterrupted power supply system.

Depending on the imposed functional requirements, the specialized seismic stations of the TWS can be divided into two types: auxiliary (regional) and basic (reference). The characteristic peculiarities of the auxiliary and basic seismic stations are as follows.

Purpose. The auxiliary seismic station is basically intended to protect populations or coastal regions from local tsunamis with relatively low tsunami danger and to supplement the SO TWS for the purpose of its optimization.

The basic seismic station constitutes the basis of the SO TWS and is intended to protect populations, critical facilities, or coastal regions from local tsunamis of high danger level.

Equipment complex. An auxiliary seismic station of the SO TWS should usually be equipped with two broadband three-component seismic signal sensors (a velocimeter and an accelerometer).

A basic seismic station of the SO TWS should be a seismic group with dimensions of 15 to 25 km or more. The central point of the group should be equipped with a broadband velocimeter and accelerometer; remote points are equipped only with accelerometers; the central point should be equipped with a system for seismic data collection and processing in automatic ànd automated modes, as well as with a system for technological communication with distant points.

Implementable functions. Auxiliary seismic station of the SO TWS should provide the TWS with seismic data at the level of decision making about the possibility of a tsunami on the basis of the network of stations, as well as recognition of strong earthquakes in the automatic mode, and provide warning to the local system for informing a population of an occurring strong earthquake.

A basic seismic station of the SO TWS (on the basis of its data alone) should provide for decision making about the possibility of a tsunami from earthquakes in the near zone (up to 200 km) in the automatic ànd automated mode; send a warning to the local system for alerting the population about occurring strong earthquake and the possibility of a tsunami; and provide the TWS with seismic data on the level of decision making about the possibility of a tsunami on the basis of the network of stations.

Working regime. An auxiliary seismic station of the SO TWS should operate in continuous automatic and automated modes, and constant staff presence is not required.

A basic seismic station of the SO TWS should operate in continuous automatic and automated modes with a constant around-the-clock presence of highly qualified staff.

The main parameters of observation systems in seismology are the number of stations; geometric configuration of their network; characteristics of locations of individual stations; frequency characteristics of seismometric channels; and their dynamic range and transformation coefficient. Due to economic reasons, the number of stations in the SO TWS is limited, which, in turn, requires solutions to the problem of the optimal planning of this network.

The number of seismic stations of the SO TWS required for reliable decision making about the possibility of a tsunami is determined by the requirements for complete solution of the inverse problem: estimation of the main parameters of earthquakes from recordings of seismic signals by a network of seismic stations. In the deferred mode, it is usually solved by recordings from 15 to 40 stations at a great distance from the source. But this approach is not applicable in solving the tsunami warning problem because of the

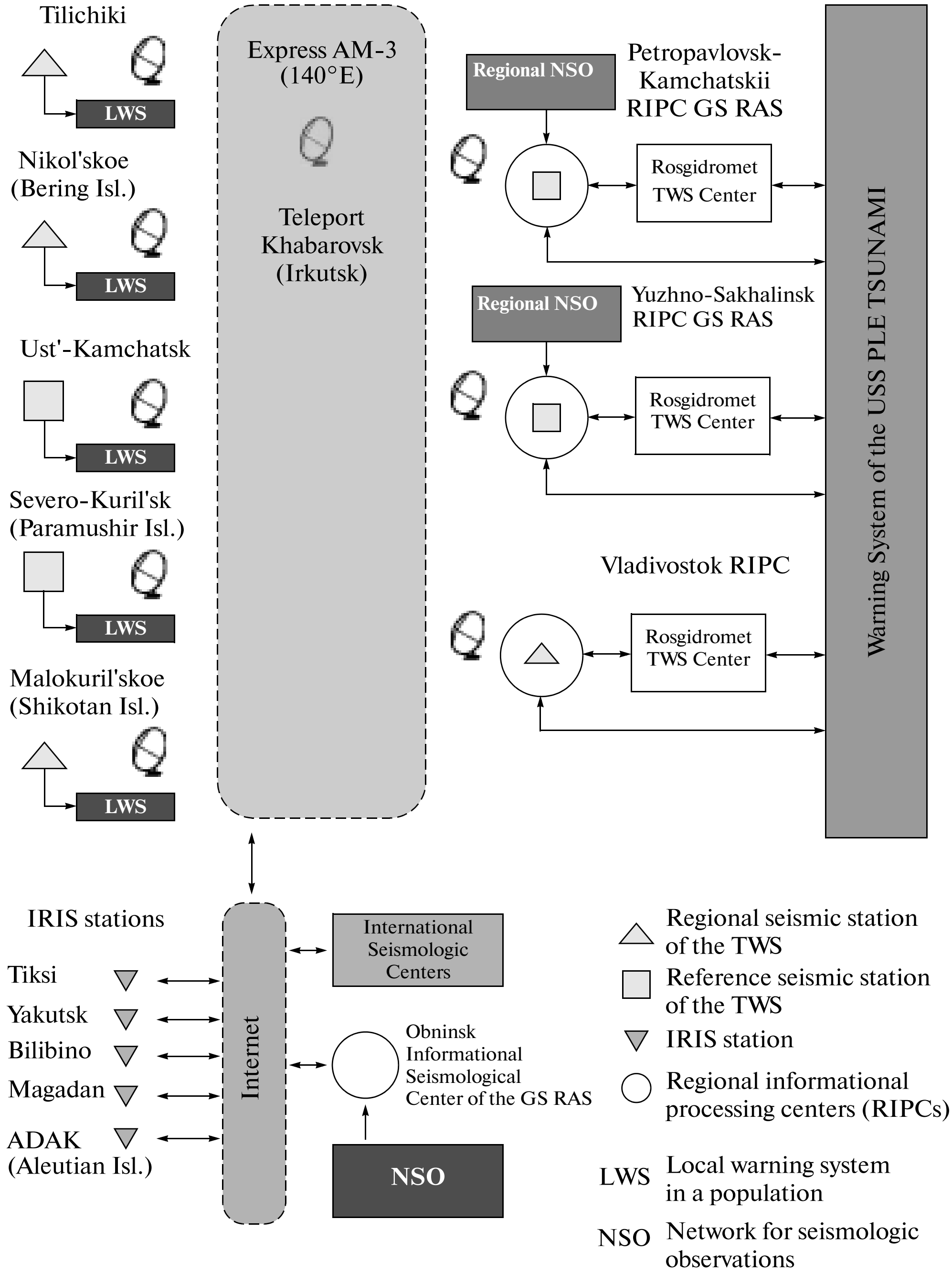

Fig. 1. Structure of seismologic observation network for the TWS (first stage).

small time reserve, which is less than 10 min. Therefore, we have to rely on the use of close stations only. However, in principle the use of several tens of stations near the source could yield relatively more reliable results, but this approach is economically unrealistic. As a reasonable compromise, we can consider the establishment of 15–25 stations in the limits of the Russian Far East, 10 to 12 of which should be located near the possible epicentral zones of the tsunamigenic earthquakes and have high survivability, while the rest can be of the usual regional type. In this case 3 to 5 stations will usually be in the direct proximity of the source of a given earthquake. Figure 2 shows the planned scheme of location of specialized seismic stations of the TWS on the territory of the Russian Far East and the stations of the global digital GSN network, participation of which is needed for refining the the possibility of a tsunami decision.

The initial data needed for generating the tsunami warning are the data from continuous three-compo-

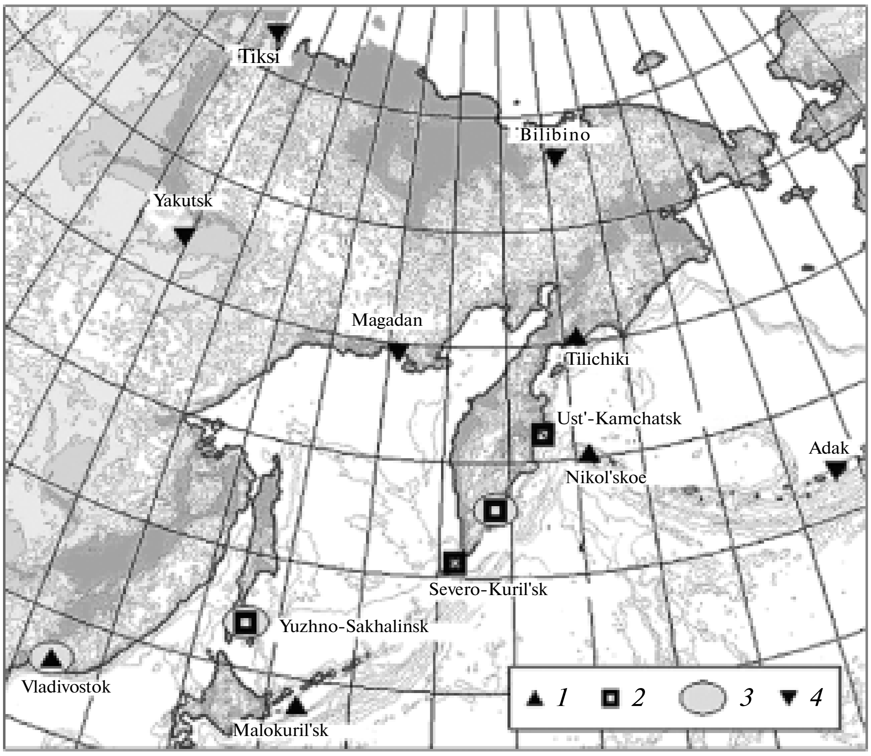

Fig. 2. System of seismologic observations for TWS with involvement of stations belonging to IRIS global network for refining decisions on the possibility of a tsunami. (*1*) Auxiliary seismic station, (*2*) basic (reference) seismic station, (*3*) regional centers for data collection and processing, (*4*) stations belonging to IRIS global network

nent recording of ground movements in a wide range of periods (frequency range no less than 0.01 to 20 Hz). It is fundamentally important to provide sufficient dynamic range of the system (no less than 120 dB). It must record ground accelerations up to 1000 to 2000 cm/s^2 and velocities up to 200 cm/s without distortion, and should have sufficient survivability and vibration immunity, mechanically withstanding the mentioned accelerations and not creating crosstalk among the components. Only the accelerometers can record the maximal possible seismic signals without distortion. To solve the problem of tsunami warning together with monitoring the seismicity of the region as a whole, each seismic station must be equipped with a velocimeter able to record weak and moderate seismic signals and an accelerometer for recording the maximal possible seismic signals (up to 2*g*).

It is advisable to use borehole sensors for solution of the TWS problems. The sealed borehole is characterized by small oscillations in temperature and pressure, which are usual noise sources in the sensor frequency range. The variant of placing the sensor in a borehole is preferable also because of the substantial decrease (to 20 dB at 15 to 20 m depth) in surface anthropogenic seismic noise. In addition, the cost of a borehole is less than building facilities with adequate conditions in relation to temperature and pressure changes needed for creating conditions suitable for broadband seismometers. Sensors should be selected in a version for boreholes with a possible water column height of 25 m.

In order to equip the TWS seismic stations, sensors of the Güralp company are proposed. For the velocity channel, the basic demands are best satisfied by a special version of the CMG-3ESPCB broadband electronic seismometer with a decreased value of the transformation coefficient. For the acceleration channel, a CMG-5 force-balance accelerometer will be used. Accelerometers are available in both borehole design and for base installation.

Basic and auxiliary seismic stations of the SO TWS should primarily be located at the existing stationary facilities of the GS RAS and in those populated areas where the potential tsunamigenic earthquake sources are located in direct proximity to the given population; these are, first of all, the populations of Severo-Kurilsk, Ust-Kamchatsk, Nikolskoe, and Malokurilskoe. In addition, the reference seismic stations of the SO TWS should be combined with the regional information processing centers (IPC) of GS RAS and the TWS centers of Rosgidromet in the Russian Far East.

The emergency power supply system at each auxiliary and basic station and IPC should include two levels. The first level is constructed using an uninterruptible power supply, to which all station elements, namely, the recorder, server, operator workplace, and so on are connected. The time of maintaining the network elements of the first level in a working state should be no less than 12 h. The second level is built from autonomous electric diesel generators, whose power is calculated in each case with allowance for supplying emergency lighting, facility heating, and other domestic needs.

Communication system for data transfer

The peculiarities of seismic data processing include the fact that the data from many stations must be processed jointly in order to obtain the earthquake source parameters (epicenter coordinates, depth, magnitude, and so on). This leads to the need for organizing the data transfer from the seismic stations to the regional IPCs in real time. Transfer regimes and the volume of transferred data are primarily determined by problems of observation system (this network is either specialized for tsunami prognosis or it also performs other seismic monitoring functions); however, they also depend significantly on the technical capabilities existing in a given country or region. In the specific economic and geographic conditions of the Far East region, a full-scale data transfer system providing a continuous transfer regime for a complete three-component seismogram from the seismic stations to the processing center can only be built on the basis of satellite communication channels.

The handling capacity of the communication channel needed to transfer the full array of data is at least 32.0 Kbit/s for an auxiliary station and at least 64.0 Kbit/s for a basic station.

In order to increase system reliability, it is advisable to provide reserve communication channels (telephone, telegraph, telex, radio channels in the UHF and HF ranges) satisfying the requirements on reliability, readiness coefficient, and channel access time for transferring the main seismic signal parameters (arrival times of S and P waves, maximal amplitudes, and recording periods). In this variant, the transferred data volume decreases by 4 to 5 orders of magnitude, constituting no more than 50 to 100 bytes per event while satisfying quite high demands on speed (delay of no more than 1 to 2 min) and channel readiness coefficient (at least 0.99).

Information processing data centers of the seismic station network

From the viewpoint of solving the main TWS problem, which is operational tsunami prognosis, only strong events with magnitude higher than the established threshold value ($M > M_{thresh}$) should be selected automatically for processing in real time. On the other hand, rapid obtaining of data on the maximal possible number of regional events yields an effective solution to secondary problems of the SO TWS. It is obvious that achieving the optimal combination of both problems in a single system is far from easy. At the first level we should limit ourselves to providing the best conditions for solving the main TWS problem, and in the course of its implantation, transition to solution of other problems.

At the present time, to generate a tsunami warning in the Kurile–Kamchatka zone, the threshold value of the magnitude (M_{thresh}) is taken as 7.0. Such earthquakes are quite rare events; in this zone they occur on average one or two times a year (from data for 1950 to 2005). A substantial number of weaker earthquakes ($M > 4.0$) are involved in processing for the “urgent message” service.

The pwrocessing system of the SO TWS can be either centralized or distributed. In conditions of the Russian Far East, the seismologic data processing system must be constructed on the basis of the regional IPCs of the Geophysical Service of the RAS. The regional IPCs in Petropavlovsk-Kamchatskii and Yuzhno-Sakhalinsk must solve simultaneously (in parallel) the problem of the possibility of a tsunami on the basis of data from all the seismic stations that are involved in the tsunami warning service. At the present stage of evolution of a seismological observation system for the TWS, it is advisable to organize reception and processing of data in the automatic mode in Vladivostok on the basis of the Rosgidromet TWS center. Processing results from all the IPCs should be automatically displayed on the situation panel of each IPC and be used for monitoring in the decision making stage. This algorithm for data processing and the possibility of a tsunami decision making can be implemented under the condition of creating equal and full access for all the IPCs to the data from all seismic stations and the processing results from other IPCs. In essence this implies the creation of a combined information space in real time on the basis of satellite communication channels. This requires, specifically, backup of the performance of the functions of each IPC in case of failure (catastrophic earthquake, technical malfunctions).

Full data on an earthquake from all the seismic stations of the Far East region will be received at an IPC 3–5 min later than it will be recorded at the station closest to its hypocenter. Thus, the most reliable decision on the possibility of a tsunami will be made with a 5–10 min delay in comparison to the moment of decision making at the auxiliary and basic SO TWS stations closest to the earthquake hypocenter.

Due to the extremely nonuniform temporal distribution of the number of seismic events arriving at the system input, it is necessary to distinguish several processing levels differing with regard to regime, implementation time and frequency, set of data being used, software and required calculation resources, and degree of need for operator participation. We can distinguish five main processing levels.

1. Preliminary processing of seismic signals (adaptive optimal filtering for the purpose of increasing the signal-to-noise ratio, polarization analysis, and so on); monitoring the effectiveness of seismometric channels. Level 1 must be performed automatically in *real time*.

2. Extraction of seismic event signals from every channel of seismic data entering the IPC and determination of the parameter set of extracted signals (arrival time, predominant period, amplitude, and so on). Level 2 must be performed automatically in *real time*.

3. Association of distinguished seismic phases, declaration of event, first (preliminary) determination of its main parameters (time, source coordinates, magnitude), check of geographic and magnitude criteria in order to detect potentially hazardous tsunamigenic events. This level must be performed in automatic and/or automated *quasi-real time* regime (acceptable lags from start of earthquake recording at the station until start of level 3 is no more than 1–2 min, and the appearance of unprocessed events in the queue system is not acceptable).

4. Refinement of the main parameter set (in particular, source depth and magnitude) in network of stations for all sufficiently strong (with magnitude $M > M_{alarm}$, where M_{alarm} is the alarm magnitude level) regional earthquakes, and determination of additional tsunamigenicity criteria and signs. Estimation of earthquake tsunami danger from ensemble of seismologic criteria (primarily the $M > M_{thresh}$ criterion). Decision making about "tsunami warning" signal issuance in interactive urgent regime. The allowable time from the onset of earthquake recording at the station to completion of all operations is 7 min at most. The primary processing mode is automated (with operator participation).

5. Revision of all earthquake parameters with involvement of data from the world network stations. Transfer of processing results to regional tsunami warning centers and to the TWS centers of Japan, the United States, etc., must be performed in the automated mode. The allowable delay time from the onset of earthquake recording at the station is 20 min at most.

The principles of design and functioning of the TWS imply two regimes of its operation, namely, *standard* and *alarm*. It is obvious that the first, second, and third levels correspond to the standard regime, while transition to the fourth level (and then to the fifth level) means transition to the alarm regime. The requirement for rapid determination of the parameters of events that take place at random moments of time leads to the need to organize processing of levels 1–3 in real time. The events that arise at random moments of time must be processed sequentially, one after the other, in the order of their arrival to the system input. The processing time must be comparable with the maximal possible event frequency. The last condition imposes severe requirements on the operating speed of the algorithms that are used for initial evaluation of the parameters of the occurring events, nonperformance of which may lead to creation of queues of unprocessed events, which in application to TWS problems is unacceptable.

Tsunami warning with strong earthquake sources in near zone

The problem of local tsunami warning when a strong earthquake occurs beneath the ocean floor in immediate proximity to the shore (up to 200 to 250 km) can be solved rapidly (but inevitably with incomplete reliability) from the a priori limited data of a specialized seismic station located in a protected populated area or in its vicinity. The delay time from the onset of earthquake recording at the station until making a decision on the possibility of a tsunami (the reaction time) is based on epicenter and magnitude estimates of the subject earthquake, which requires a specialized seismic TWS station that includes several components:

– formation time of tsunamigenic earthquake source (no less than 30 s; 110 s in typical cases; up to 550 s in rare cases);

– delay time of informative groups of seismic waves (transverse waves, Rayleigh and Love surface waves) from moment of P wave arrival (determined by distance from source to station, namely: 32 s with 200 km distance; 48 s with 300 km distance; 80 s with 500 km distance; and 160 s with 1000 km distance; it is assumed that the group velocity of the Rayleigh wave is 3.5 km/s and average velocity of P waves is 8 km/s);

– time of formation of tsunami hazard signs on the recording, primarily a maximum in the surface wave group (no less than 40 s, 100 s in the typical case, and up to 200 s and more in rare cases);

– time for processing seismic signal, analysis of informative parameters, and output of warning signals (up to 45 s).

In order to decrease reaction time, specialized techniques, algorithms, and software must be developed.

The tsunami danger warning signals that are generated in the automatic mode at the specialized TWS seismic station must be transmitted to Ministry of Emergency Situations subdivisions, to the local population area warning system, and to the administration of the corresponding level.

The main approaches to generating tsunami warning signals in conditions of severe lack of time with strong earthquake sources in the near zone are the following.

1. Use of rapid estimates of oscillation amplitude level or automated estimate of macroseismic intensity on the basis of specialized analysis methods using incomplete data from a single three-component broadband station or group of stations and, if necessary, decision making on this basis only.

From the results of studies [Solov'ev and Poplavskaya, 1982; Poplavskaya, 1984] of 124 cases of tsunami occurrence from strong earthquakes in the Russian Far East in 1952 to 1976, it has been shown that the probability of tsunami occurrence in a population or a coastal region where a perceptible earthquake is manifested increases as the intensity of quakes increases. With $I = 6–7$ points on the MSK-64 scale, tsunamis occur in six out of ten cases; with $I = 7–8$ points they occur in nine out of ten cases.

During studies performed in 2007, Poplavskii showed using catalog data for the 1737–1997 period that with quake intensity $I > 7$ points, the probability of tsunami occurrence with a washover height of $h > 1$ m is more than 0.7. Operational estimation of macroseismic intensity of a strong nearby earthquake from station recording needs further examination. We should also exclude cases of very nearby quakes with $M = 4.5$ to 5.5, for which duration of oscillations is small.

2. Use in large populations or on objects of higher responsibility of seismic groups (basic seismic stations). The data of a seismic group can provide relatively fast location of the earthquake source that is substantially more reliable than from the data of a single station.

3. Use of data from regional seismic station networks. Regional seismic station networks in the Russian Far East can rapidly give additional information on earthquake source location when there is real time access to their data. Currently this is possible primarily at Kamchatka, where there is a radiotelemetric network.

4. Use of knowledge on the spatial and temporal regularities in distribution of strong earthquake sources in the Kurile–Kamchatka seismofocal zone.

5. Organizational and administrative measures relating to education and training of the population that are directed to improving the readiness for action when there is tsunami danger. In particular, the population and authorities of a coastal population should begin evacuation immediately, not waiting for a warning signal from the TWS when an earthquake with intensity $I = 7$ points or more on the MSK-64 scale is felt.

Each specialized seismic station and seismologic observation network of the TAS in general should operate in the iterative regime, repeatedly improving earthquake parameter estimation at every iteration in accordance with the new information obtained at a given moment. First estimates necessary for decision making on the possibility of a tsunami at the local level must be obtained in the course of no more than 1–3 min after the onset of earthquake recording.

The sequence of actions of the seismologic observation system after tsunami warning at the local level with sources in the near zone is as follows:

– generation of a warning signal on the possibility of a tsunami in the automatic mode on the basis of the first estimate of earthquake intensity from recorded amplitudes of the seismic signals of P and/or S waves at the specialized auxiliary or basic seismic station of the TWS located in the territory of protected population or in its environs. Delay is 3 min at most;

– confirmation or rejection of a signal on the possibility of a tsunami in automatic and/or automated modes on the basis of refinement of the estimate of earthquake coordinates from groups of seismic waves and the preliminary estimate of earthquake coordinates and intensity from data of other groups of seismic waves and the preliminary estimate of earthquake coordinates and magnitude from data of specialized auxiliary or basic seismic station of the TWS located on territory of protected population or in its neighborhood. Delay is 3–7 min at most, depending on the epicentral distance and earthquake magnitude;

– confirmation or rejection of a signal on the possibility of a tsunami in automatic and/or automated modes at the level of regional IPC on the basis of refined estimates of earthquake coordinates and magnitude from data of the regional (closest three or four seismic stations) network of specialized seismic stations of the TWS. Delay is 7 min at most.

– confirmation or rejection of signal of the possibility of a tsunami in the automated mode at the level of regional IPC on the basis of refinement of estimates of earthquake coordinates and magnitude from data of the network of specialized seismic stations of the TWS in the Russian Far East with involvement of data from digital seismic stations of regional and world seismologic observations. Delay is 20 min at most.

CONCLUSIONS

1. Initial data and requirements for developing a seismic observation system for the tsunami warning service and its functions and tasks are considered.

2. The structure of the SO TWS is proposed. General technical and methodical measures and tools providing an increase in the efficiency of operational tsunami prognosis from seismological data in the Russian Far East and continuous seismic monitoring of the territory of the Russian Far East and the world are examined.

3. Implementation of the concept of the SO TWS development should provide the following:

– increase in degree of protection against seismic action for populations located on the coasts of the Kamchatka Peninsula, in the Kurile Islands, and on the shore of the Sea of Japan (coastal populations of Primorskii Krai);

– decrease in delay time for population warning about the possibility of a tsunami by seismologic data from the onset of earthquake recording to 3 min for intensity of quakes on the local level, to 7 min at the regional level, and no more than 20 min at the interregional level;

– decrease in number of false tsunami alarms.

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