MAIN FEATURES OF LOCAL TSUNAMI FORECAST FOR THE COASTS OF KAMCHATKA AND THE KURIL ISLANDS*

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INTRODUCTION

Most epicenters of tsunamigenic earthquakes in the Pacific Ocean are concentrated in ocean areas with depths from 0 to 5000 m (Figure 1). Often these earthquakes occur close to the coastline and settlements. There are situations when a strong tsunami strikes a settlement, but the operative Tsunami Warning Service (TWS) is not able to warn people about an impeding disaster because of lack of time. We call such cases as "fatal tsunami omission". We have found a few conditions which, when fulfilled, can reduce a number of such cases to a reasonable minimum.

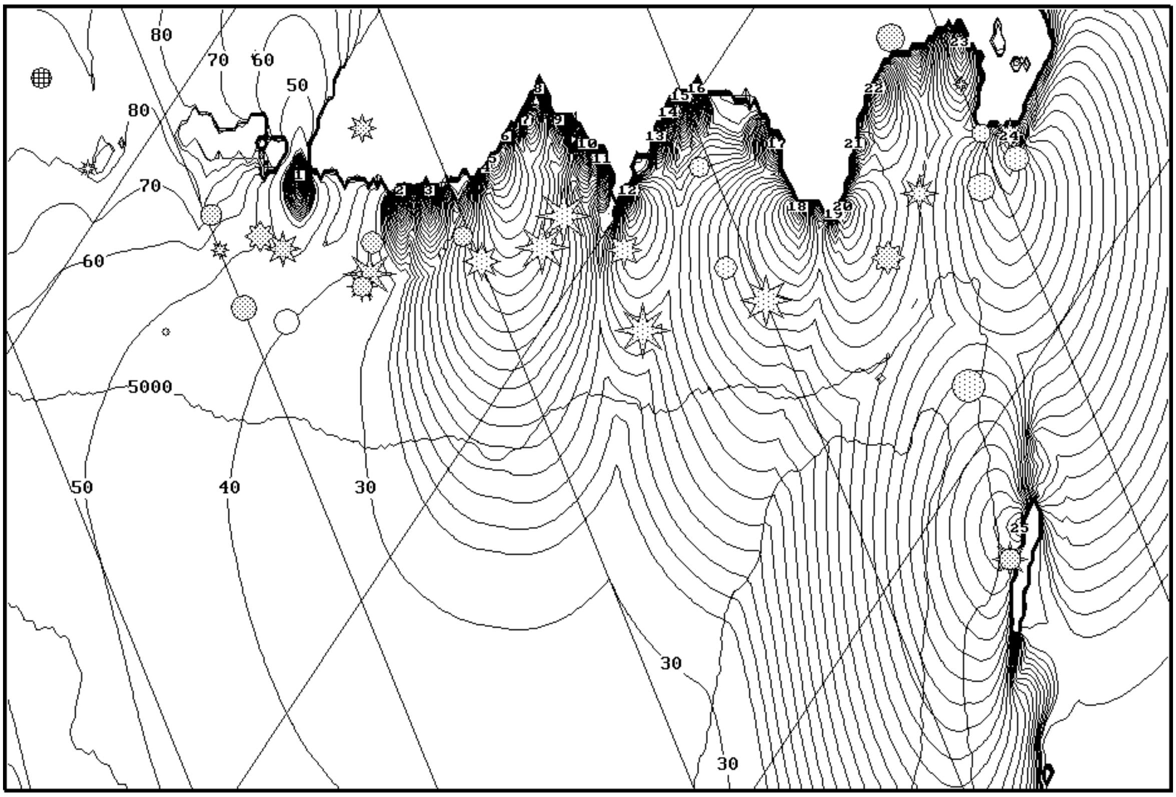

Figure 1. The Pacific Kamchatka coast and adjacent ocean, with depth contours of 0 and 5000 m. Tsunamigenic earthquake epicenters for the period 1737 –1982 are marked by circles and stars. The "diagrams of minimum expected tsunami arrival time" are shown for 25 coastal sites; the TWS dead zones for each of these sites are distinguished by more frequent isolines (every 1 min). Broken lines, crossing time isolines, mark their "responsibility regions".

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1. PROGRAM FOR NUMERICAL TSUNAMI SIMULATION

In this work, we used the computer program for numerical tsunami simulation, developed by Fine and Kharmushin [see Poplavsky *et al.,* 1997]. A brief description of this program will clarify the results given below.

This program allows calculation of tsunami propagation time from a location and plots a map of isochrones. If this location is in the area of the tsunami source, we call the corresponding calculated time as the "tsunami propagation time". If the point is a site where the wave arrives from an unknown source, the time will be called as the "tsunami expected time". The corresponding isochrone map gives the information about tsunami propagation time to this location from any other point of the respective water basin.

This program enables us to calculate tsunami expected time simultaneously for a number of points. The program selects the minimum time for each node of the calculation area and represents the results as a system of isochrones. In this way we construct the isochrone map of the minimum expected time in the vicinity of the coast under study. Eventually, our program can be used to calculate the difference in tsunami expected time for two non-overlapping ensembles of points and to represent them as a system of fixed-difference isolines.

2. ADVANCE TIME FOR TSUNAMI ALARM

The central idea in our problem is the concept of the "advance time for the tsunami alarm". This question was analyzed in details by Poplavsky *et al.* [1997] and Poplavsky [2001]. We assume that the alarm may be considered as being sent to a certain settlement in advance if the respective information arrives to this settlement before the wave arrival, in time to evacuate people inland from the sea-shore.

We also introduce the notion of the "period of the alarm regime" ("alarm period") as the entire period from the beginning of a major earthquake to the complete evacuation of the people. It is obvious that only the sites with the expected tsunami propagation time greater than the named alarm period will receive an advanced alarm. This alarm period may be divided into four non-overlapping time periods.

t_p is the minimum propagation time of the P-wave from the seismic source to the TWS seismic stations.

Δt_1 is the duration of the TWS reaction to the seismic event; it ends by issuing the alarm notice to the covering areas;

Δt_2 is the duration of the alarm transmission via communication lines, which ends with the alarm signal at the settlements;

Δt_3 is the duration of people evacuation.

The sum of these intervals,

$$t_{\min} = t_{\mathrm{p}} + \Delta t_1 + \Delta t_2 + \Delta t_3$$

gives us the minimum expected time, which allows receiving the alarm notice in advance.

The condition

$$t\ (i,\ tsunami) \geq t_{\min}$$

is the advance condition for the earliest tsunami forecast at sites $i = 1, 2,\ldots, I$ (i is the site name). Here $t\ (i,\ tsunami)$ is the tsunami expected time at site i. This condition for fixed Δt_1,

Δt_2, and Δt_3 values enables us to determine geographic TWS "dead zones" for any point (settlement) i of the seacoast. The dead zone is the area of the sea confined by the isochrone of the expected tsunami time $t_{\min}$ for this site. This area is the area of possible tsunami sources, which will inevitably be omitted by the TWS at site i.

An example of such dead zones for 25 settlements on the Pacific coast of Kamchatka for $t_{\min} = 27$ is shown in Figure 1. Here we took $\Delta t_1 = 10$ min, $\Delta t_2 = 2$ min, $\Delta t_3 = 15$ min and neglected time $t_p < 1$ min. We presented isolines of minimum expected tsunami time for all these sites. Inside the dead zones the isolines are plotted every 1 min. For the expected time greater, than 27 min, the isolines are plotted every 10 min.

As we can see in this Figure, the areas of the dead zones for different sites are very different. The maximum diameters of these zones are from 10 to 300 km for the Pacific coast of the Russian TWS responsibility. We can also see in this figure that the unfavorable situations occur for a few settlements when a real tsunamigenic earthquake takes place inside the dead zones. It is obvious that for any site the probability to be found in such zones is higher for larger zones. Therefore, the dead zone size for a selected coastal site is the specific characteristic of the relative safety from fatal tsunami omission. Figure 2 shows the allocation of this safety characteristic along the Pacific coastline of the Kuril Islands. Empty, grey, and black circles mark the sites with dead zone diameters < 100 km, 100-200 km and > 200 km, respectively. Such schematic maps may be used for economic development planning of the coastal regions.

3. UNCONDITIONALLY DANGEROUS DISTANCE IN CASE OF TSUNAMI

If a strong earthquake occurs in the vicinity of any settlement, naturally this settlement would not be able to receive the alarm in due time. However, such earthquake itself is a serious indication of a possible tsunami, and this fact gives hope for rescuing the people.

We have introduced a term of "unconditionally dangerous distance" R for tsunamis. This is the maximum distance where the macroseismic criterion of the tsunami risk after the earthquake may be successfully used [Soloviev and Poplavskaya, 1982a,b]. It is possible to formulate this criterion for the Kamchatka and Kuril coasts as follows: a strong tsunami is highly probable at those coastal sites where the earthquake magnitude is 7 or higher, according to the macroseismic scale MSK-64. The distance, where this criterion is effective, has to be smaller than 100 km. So, the unconditionally dangerous distance for tsunami at Kamchatka and the Kuril Islands is $R \sim 100$ km.

Our objective can be solved if we can exclude unfavorable situations when the macroseismic criterion does not apply (the earthquake takes place at the distance greater than R), and the TWS has no time to deliver the alarm to certain settlements (the tsunami source crosses their dead zones). This can be attained, if the unconditionally dangerous distance R will include the dead zone for each coastal site.

Most of our coasts satisfy this condition. However, there are also sites, which do not satisfy it. In every such case the minimum expected tsunami time $t_{\min}$ has to be decreased from 27 min to the minimum tsunami propagation time at the distance R in the vicinity of and in the direction to the respective settlement. Such time reduction will require increasing of the TWS operation efficiency and enhanced mobility of the population.

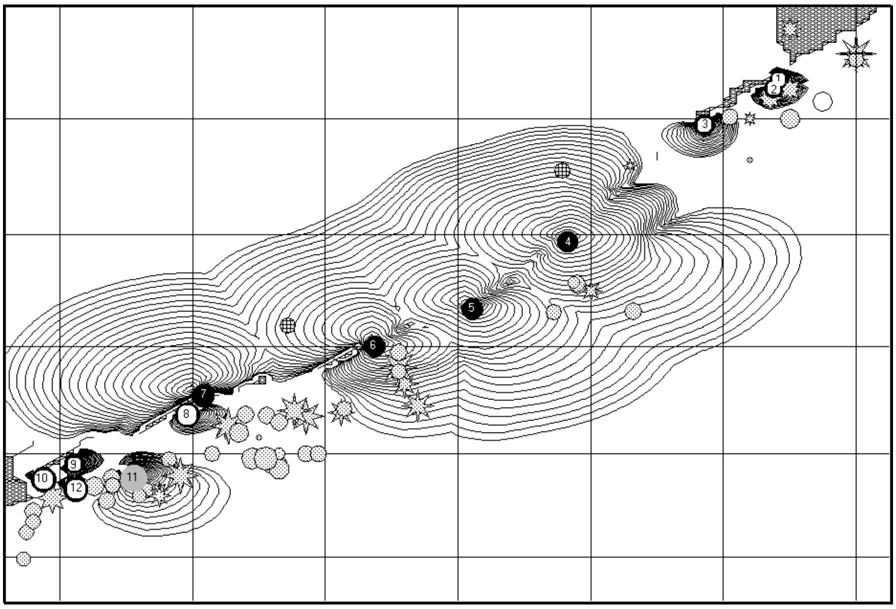

Figure 2. Zoning of the Pacific coast of the Kuril Islands, depending on the frequency of fatal tsunami omission.

4. MAIN HIGH-SPEED TRACKS FOR TSUNAMI PROPAGATION

Our program calculates the expected tsunami arrival time at *N* points. It associates the minimum arrival time with each grid node of the model domain. Each node (the tsunami source) therefore corresponds to one of the *N* points (surrounding this node) where the tsunami wave will arrive first The set of these nodes, which provide the minimum expected time for tsunami arrival to site *i*, form the “responsibility region” for this site. Size and configuration of such regions depend on the number of points *N* where the minimum tsunami expected time is calculated. They also depend on the location of these points, and obviously, on the bottom relief of the basin.

Figure 1 shows such regions near the Pacific coast of Kamchatka (they are bounded by solid lines that cross the expected isochrones). An interesting peculiarity of this basin is that it is composed of responsibility regions for only a few sites, specifically for sites 5, 12, 18, 20, 24 and 25. This means that a tsunami wave reaches these very sites before the others for almost any location of the source.

We have thus selected the boundary points of the fastest tsunami tracks near Kamchatka. These are also the best sites for sea level measurements near the coast, as is shown in Figure 3. This map presents us expected time difference for site 8 (Petropavlovsk-Kamchatsky) and for the other sites mentioned above. This figure clearly demonstrates that tsunami waves arrive at these sites much earlier than to Petropavlovsk-Kamchatsky almost independently on the location of the source.

If we select any point near the coast and fix the expected time difference between this point and an ocean point, we can find that there is an optimum position of this ocean point providing the minimum area encircled by the isoline of this difference. For certain simple bottom topographies (constant depth, inclined bottom, striped bottom) the existence and uniqueness of such minimum can be proved analytically [Bernstein, 1992]. Such minimum also exists for any realistic bottom relief, as it is clearly seen in Figure 4. This figure shows 27-sec time-difference isolines between Severo-Kurilsk and sites 26, 28, and 32. The isoline of the expected tsunami time-difference between Severo-Kurilsk and site 28 enclose a smaller area then the isolines for sites 26 (near Severo-Kurilsk) and 32 (farther away). Actually, based on this property, we can find out the optimum deployment sites for sea level gauges for each

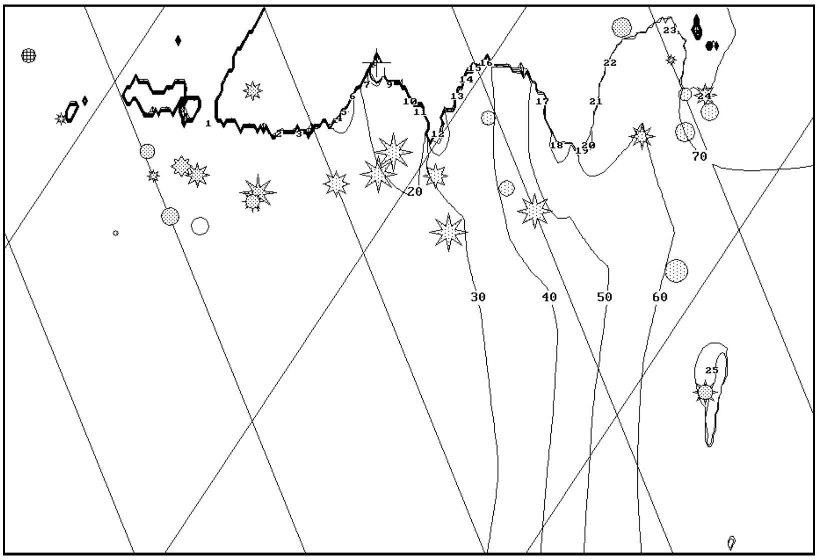

Figure 3. Expected tsunami time differences at site 8 (Petropavlovsk-Kamchatsky) and at sites 5,12,18,20,24, and 25.

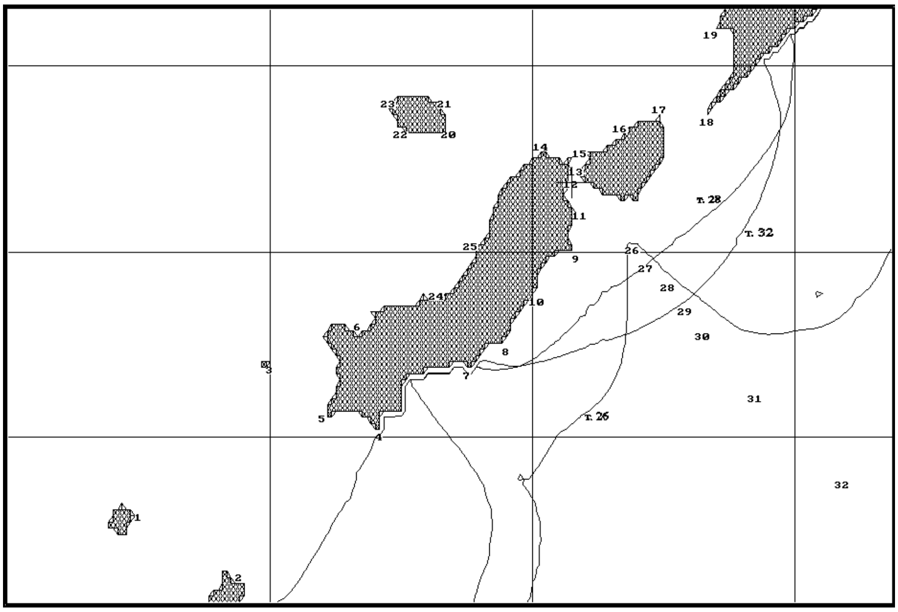

Figure 4. Isolines of the expected tsunami time difference of27 min at Severo-Kurilsk and at sites 26, 28, and 32.

boundary point described above in the areas of their responsibility areas. Apparently, the same sites will also be nearly optimal for all other locations of the examined coastline.

CONCLUSIONS

The main condition ensuring a minimum number of fatal tsunami omissions is that the diameter of the TWS dead zone for each settlement does not exceed R ~100 km. This condition can be fulfilled if the TWS response and population reaction time at certain sites can be significantly reduced.

For a fixed $t_{\min}$, coastal sites have the largest dead zones for the boundary points of the high-speed tsunami tracks. These sites are preferable for deployment sea level gauges near the sea-coast, because tsunami waves arrive there earlier than at the other coastal locations.

Apparently, the open-ocean monitoring sites, which are optimal relative to the named boundary points, will also be nearly optimal for the entire coast.

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