

Mathematical Modeling in Application to Regional Tsunami Warning Systems Operations*

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Abstract. Catastrophic tsunamis that flooded the ocean coast in the past had taken many human lives and destroyed the infrastructure of the coastal areas in the Pacific and elsewhere. Recent tragic events in the Indian Ocean motivated governments to develop new and improve the existing tsunami warning systems capable to mitigate the impact of catastrophic events. In the future, regional tsunami warning systems will be integrated into a network including both the systems currently being developed and the existing warning systems (in the past, tsunami warning systems had been deployed to protect the coastal areas in Japan, USA, Russia, Australia, Chile and New Zealand).

The present study, conducted by the Institute of Computational Technologies in collaboration with other research institutes in Novosibirsk, is directed to the design of a new generation of the tsunami warning system for the Pacific coast of Kamchatka. The main purpose of the present study is to develop the computational methodology allow us to build a database of potential tsunamigenic sources that impose the imminent tsunami risk for the eastern coast of Kamchatka Peninsula. In the first stage of the project, a set of basic model sources of tsunamigenic earthquakes is defined. These model sources are used to calculate the initial water elevation in the source area that are used as initial conditions for dynamic modeling of tsunami propagation in the selected geographical region near the Kamchatka east coast. The next stage is the modeling of propagation and transformation of tsunami waves on the way from the source area towards the coast. This information is presented as a decision support system intended for use by persons on duty who are responsible for initiating tsunami mitigation procedures such as evacuation of people and sending ships away from the dangerous harbors and bays.

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The project involves numerical solution of a large number of instances of wave hydrodynamics problems. At the same time, interpretation of the results requires non-trivial postprocessing and development of a specialized information systems. Numerical calculation of tsunami propagation in the ocean with a real bathymetry for multiple combinations of the model earthquake sources with high spatial resolution constitutes the major part of the computational requirements of the project. The amount of computation resources needed for numerical modeling of tsunami propagation implies the use of high performance computers and may require adaptation of numerical algorithms to specific computing platforms.

In the future, this approach may be extended to other tsunamigenic areas in the Pacific and the Indian oceans. In the latter case, we plan to consider the problem of defining the extension of the coastal zone that is the subject for flooding by tsunami waves. This would require to perform run-up calculation. To achieve the necessary accuracy in reproducing of tsunami behavior in the coastal areas, we will need to take into account such features of the coastal area as small rivers, lakes and swamps. This will significantly increase the amount of computational resources needed both during the development of numerical models and algorithms and in the production runs.

1 Introduction

The present article is directed to the development of database of model tsunami sources that present the potential risk for the protected coastal sites located at the Kamchatka east coast. The complex of processing methods is suggested, and the principles, experience and results of numerical calculation of tsunami generation and propagation are discussed.

The database “Tsunami zoning of Kamchatka” is designed for storage, review and retrieval of information about tsunami events generated by the set of model tsunamigenic earthquakes in the recording tide gages associated with the protected coastal locations. This database is a part of the information system and works in the user-operated mode, providing selection of a set of protected coastal locations, model earthquakes, computational domain, constructed computational grid, set of parameters of computational algorithm, mathematical models of computation of initial bottom disturbance and its further transformation during the tsunami wave propagation.

A separate “research” component of the information system provides options for setting of parameters of the calculation area, set of protected coastal locations, model seismic sources, mathematical models of tsunami generation and propagation, separate components of computational algorithms, etc. This approach completely corresponds to the adopted concept of algorithmic and system support of the National Tsunami Warning System of Russian Federation. According to this concept, mathematical modeling of tsunamis is carried out by specialists on orders of other services, and modeling results are passed to customers.

In the operational mode of the National Tsunami Warning System, the estimation of the expected tsunami heights is proposed by means of numerical

modeling of dynamic impact of tsunami waves at the coast. To implement this methodology, additional algorithms of data approximation based on methods and approaches of artificial intelligence will be used. The coupling of a synthetic catalogue created in such a way with a catalogue of historical evidence and real-time information from gauges of hydrophysical monitoring of ocean surface system is assumed.

2 Technologic Basis

The proposed computational methodology includes the following technological stages.

First, the geographical area, adjacent to the protected coast (Kamchatka Peninsula) and containing zones of possible tsunamigenic earthquakes is determined. The computational domain “Kamchatka” and a set of protected points are confirmed (see Fig. 1). The position of “virtual” tide gages related to the protected coastal locations are determined. These tide gages are represented by

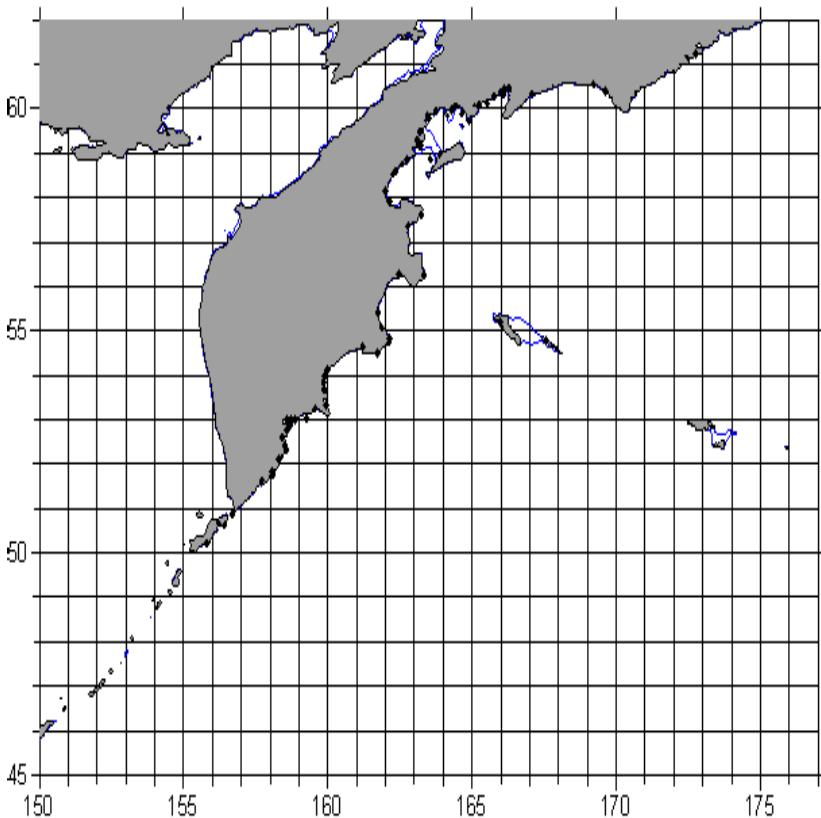


Fig. 1. Location of the protected points on the coast of Kamchatka

a set at computational points that are most closely located from the protected coastal locations. With that, depths in these points are determined and deviations of their geographical coordinates from coordinates of the actual protected locations are estimated. Usually these deviations don't exceed 2-3 angle minutes and may be considered to be quite acceptable. To estimate the spatial variability of wave behavior near a particular "virtual" tide gage, four nearby gages (2 "left" and 2 "right") are settled. The estimation is carried out by expert analysis using "external" geoinformation system software.

The study of seismotectonic features of the Kuril-Kamchatka seismic zone [4] resulted in the proposed scheme of probable locations of the possible tsunamigenic sources (Fig. 3) that present the imminent hazard for the protected villages at the Kamchatka east coast. For each model source, the initial co-seismic displacement of the ocean bottom is calculated based on the (Okada, [8]) formulas. This system is intended for usage in the research mode.

Modification of computational algorithms is carried out to calculate transformation of tsunami waves from the source domain up to the coast. Numerical algorithms were modified and adapted to the specific bottom topography and geometry of coastal boundaries. The different numerical algorithms were used to evaluate the accuracy of modeling results and degree of their stability in relation to accounting of bottom and surface frictions, Earth sphericity, nonlinear effects, and other factors that influence the tsunami propagation.

The system of control algorithms is created to provide organization and carrying out serial calculations of propagation of tsunami waves. Computational and control algorithms are also meant for realization of the "research" mode. A special data controlling system was created to adapt the basic computational output – computed mareograms at every protected coastal location. For each mareogram, maximums and minimums of water-surface elevation and wave heights (half-sums of maximums and minimums) are determined in "every protected point" for every model earthquake.

For "every protected point" maximums and minimums of water-surface elevation and wave heights generated by every model earthquake are determined. The maximum and minimum event time and index number of earthquake, which generated these extreme values, are also determined for every protected location.

After a series of extensive computational experiments, which allowed to distinguish difficulties of computational modeling and ways of their solution, it was decided to make two independent series of numerical calculations – within linear and nonlinear shallow water models. The nondivergent version of algorithm having high stability margin and approximating equations of shallow water theory in spherical coordinate system was used.

3 Protected Points and Model Seismic Sources

The Kuril-Kamchatka subduction zone is a very active convergent margin between subducting Pacific and overriding Okhotsk plate, where destructive tsunamigenic earthquakes occur on the regular basis. Historical seismicity in this area is

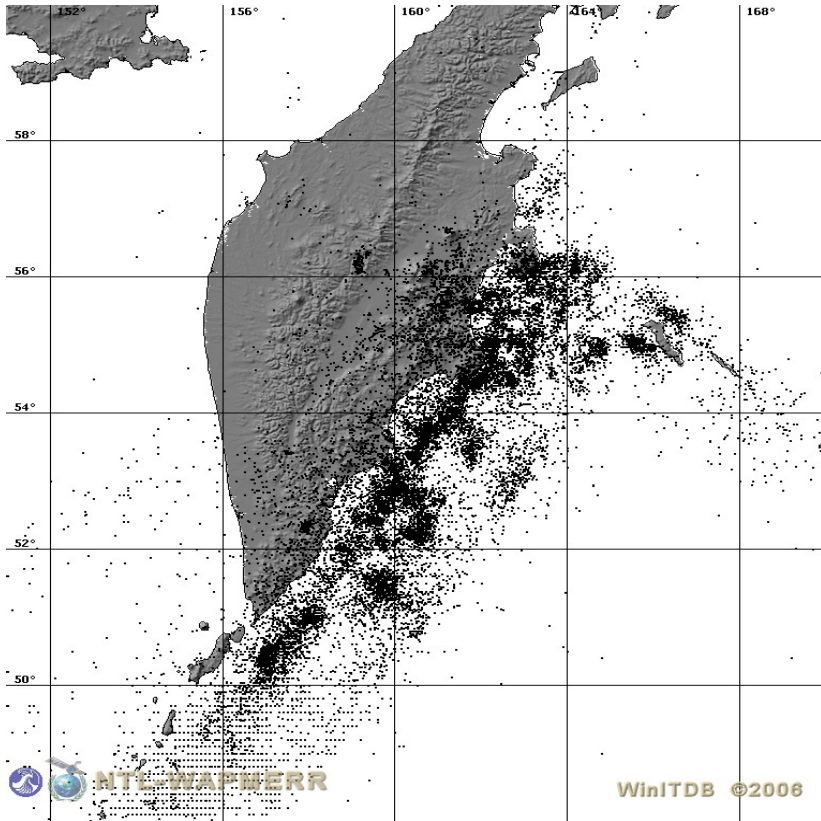


Fig. 2. Historical seismicity of Kamchatka. Nearly 23,000 of earthquakes occurred from 1737 to 2007 are shown. Source of data – ITDB/WLD [6].

concentrated within a narrow strip stretching between the eastern coast of Kamchatka and the axis of the deep-water trench (Fig. 2). In spatial distribution of this seismicity there are several local maxima that are concentrated near the main Kamchatka peninsulas. The largest historical earthquakes in this area are the 1737 and 1952 events with magnitude near 9 that ruptured the same segment of the arc [7] and generated the Pacific-wide tsunamis. Other large submarine earthquakes that generated locally destructive tsunamis at the Kamchatka east coast occurred here in 1841, 1904 and 1923.

For the study of tsunami generation, the most adequate mathematical model is the solution of a closed system of equations of the dynamic theory of elasticity, describing the oscillations of layered elastic half-space (the model of the Earth crust and the upper mantle) coupled with an overlaying compressed liquid layer (the model of the ocean). This approach to the tsunami generation was first proposed by Podypolskiy [9] and than used by Gusiakov [5]; Yamashita, Sato [11]; Ward [10]. Comer [1] has shown, that within the framework of long-wave

approximation, the solution of the fully coupled problem of tsunami generation is equivalent to the consecutive solution of two separate problems: (1) determination of static bottom deformation due to a buried seismic source and (2) calculation of tsunami propagation within the framework of the long wave theory in an ocean with the variable depth using the solution obtained at the first stage as the initial condition for the tsunami generation. This approach is widely applied in the numerical modeling of real historical tsunamis in the different parts of the Pacific and elsewhere and in the cases, when parameters of seismic source are known, allows to obtain the reasonable agreement of computed and observed mareograms.

In this model, the computed static deformation of the surface of an elastic halfspace due to an internal dislocation source is calculated based on analytical formulae obtained in (Okada, [8]) and than used as the initial conditions for the program of calculation of tsunami propagation In the ocean with a real bathymetry.

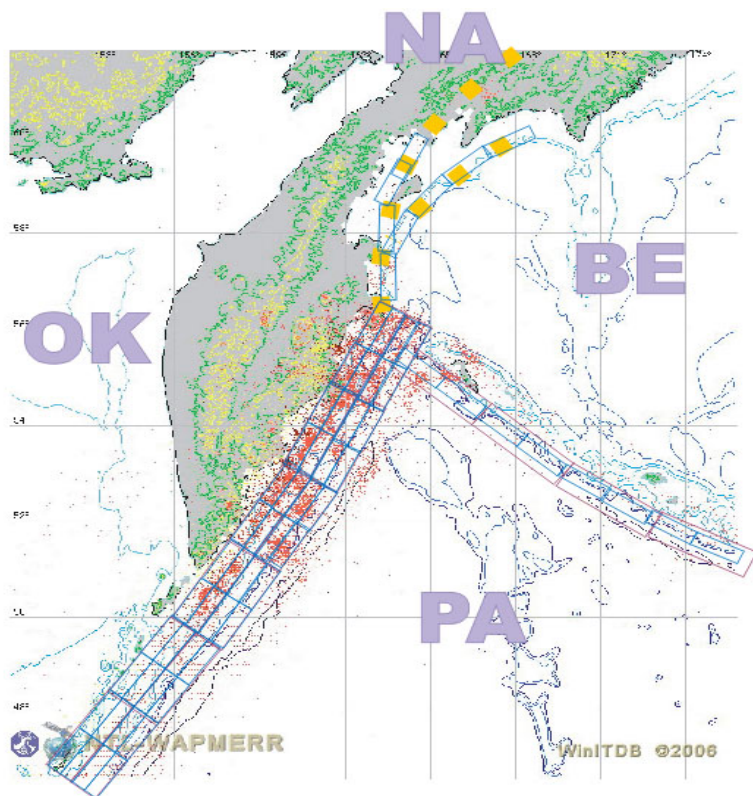


Fig. 3. Spatial distribution of the model sources with magnitude $M_w = 7.8$. Each rectangle shows the projection on the surface of the internal rupture with length $L = 108 \text{ km}$, width $W = 38 \text{ km}$

On the basis of analysis of available historical data on the tsunami occurrence in the Kuril-Kamchatka region and with invoke of expertise of regional seismologists (A.A.Gusev of the Institute of Volcanology and Seismology, Petropavlovsk-Kamchatskiy, Russia) the scheme of possible locations of potential tsunami sources was created and the source parameters for each model source were selected. The seismicity pattern was approximated by a set of equally distributed model seismic sources with parameters retrieved from regional tectonic settings and past historical earthquakes. The main set of model sources consists of 73 fault planes distributed over the area of known historical earthquakes near Kamchatka (Fig. 3) each of them is represented by a internal dislocation source. This source is described by six parameters such as length of the fault L , its width W , depth of its upper edge h_0 , dip-slip angle δ , strike-slip angle λ and amount of displacement over a fault D_0 . As a measure of intensity of such a source, its seismic moment, defined as

$$M_0 = \mu \cdot L \cdot W \cdot D_0 \quad (1)$$

According the regional seismotectonics [4], the most typical source mechanism for the major (M=7.8) earthquakes in this region is the low-angle thrust along the main interface boundary in this region – the boundary between subducting Pacific and overriding Okhotsk plates. According to this scheme, the dip angle of the fault δ is equal 15° , strike angle λ is equal 90° and the strike direction (azimuth) 58° . The spatial parameters of the model source are adopted to be as follows: length of the fault $L = 108$ km, width of the fault $W = 38$ km and displacement $D_0 = 2.75$ m. The seismic moment of this source calculated by (1) is equal to $4 \cdot 10^{10} N \cdot m$. According to the correlation formula (Aki, [12])

$$M_S = (\lg M_0 - 9.0)/1.5 \quad (2)$$

this value roughly corresponds an earthquake with the surface wave magnitude of 7.8.

4 Computational Domain “Kamchatka”

On the basis of preliminary analysis of historical data about tsunamis in water area of Kamchatka Peninsula and in accordance with the concept of designing of set of model sources the region extending from 150 to 177 degrees of east longitude and from 45 to 62 degrees of north latitude was taken as base water area. The portrait of the bottom and land relief of the region under concern is presented on Fig. 4.

5 Parameters of Model Tsunamigenic Earthquakes and Corresponding Ocean Surface Disturbances

The map of the model sources location is presented on Fig. 5.

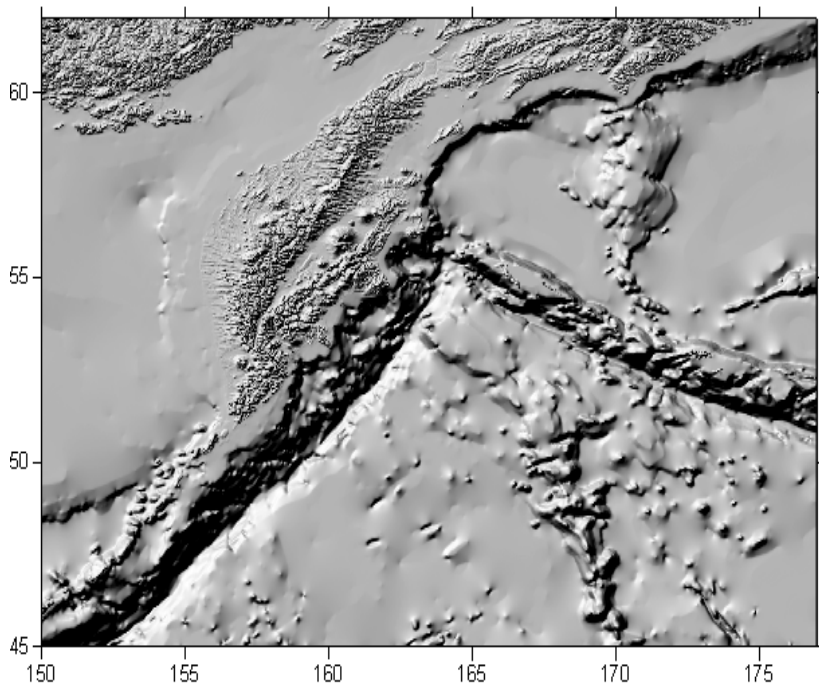


Fig. 4. Bottom relief in computational domain “Kamchatka”

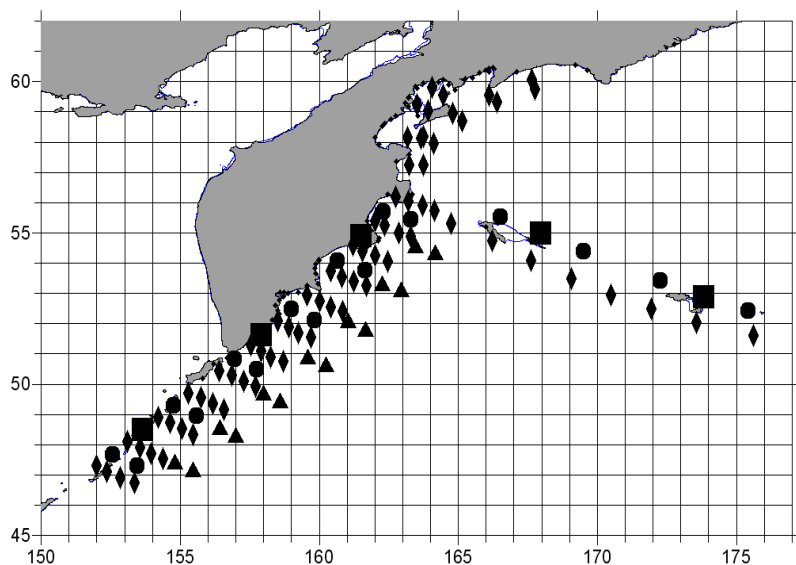


Fig. 5. Map of model sources location. Diamonds point to earthquakes of 7.8 magnitude, triangles point to 8.1 ones, circles point to 8.4 ones, and squares point to 9.0 ones.

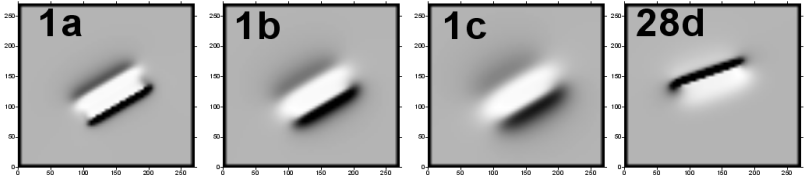


Fig. 6. Ocean surface disturbances directly above underwater earthquakes with 7.8 magnitude

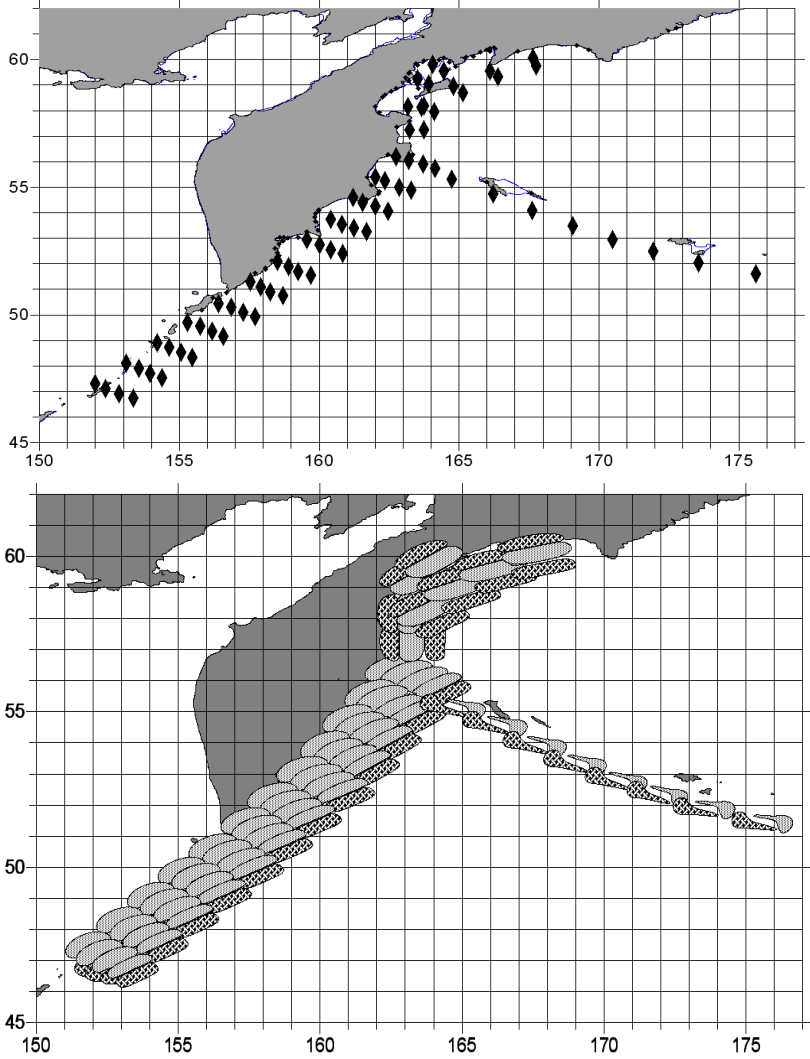


Fig. 7. Location of initial ocean surface disturbances in case of model sources with 7.8 magnitude

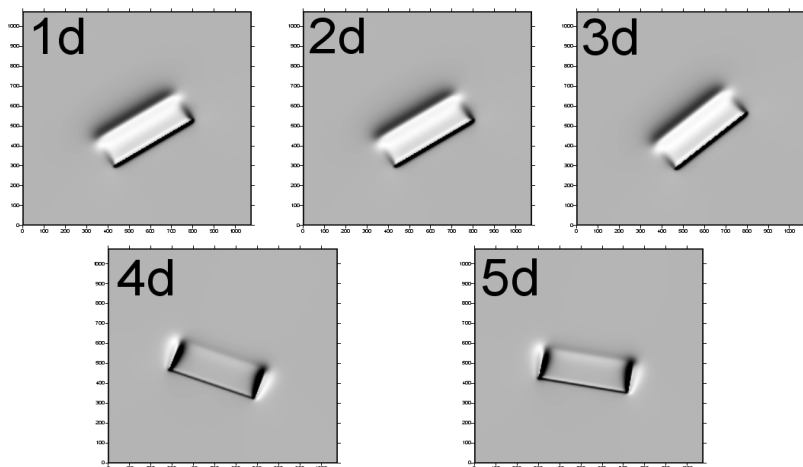


Fig. 8. Ocean surface disturbances directly above underwater earthquakes with 9.0 magnitude

Ocean surface disturbances directly above zone of model earthquakes with 7.8 magnitude are presented on Fig. 6, and map of these initial disturbances location in computational domain “Kamchatka” is presented on Fig. 7.

Ocean surface disturbances directly above zone of model earthquakes with 9.0 magnitude are presented on Fig. 8, and map of these initial disturbances location in computational domain “Kamchatka” is presented on Fig. 9.

6 Algorithms

The set of computational algorithms is divided between two modules: the module of calculation of initial ocean surface disturbance generated by model tsunami-genic earthquake and the module of calculation of tsunami wave propagation from given initial disturbance.

To carry out serial calculations the special console utility `serial_calc.exe` is developed which isn't included in package of program supporting of user-operation mode. Functionality carried out by this utility will be provided with set of utilities supporting the “research” operating mode. It should be noted that the creation of a production version of this utility required additional careful adjustment of computational algorithms and thus its development started in advance, at a stage preceding the design and realization of the database for the storage of results. Such approach was also justified, because carrying out the calculations turned out to be quite a lasting process. At this point a special computational utility `source.exe` which is meant for calculation of initial ocean surface disturbance and an utility `MassGlobalCalcul.exe` for modeling tsunami wave transformation from zone of initial disturbance up to protected points on the coast were also used.

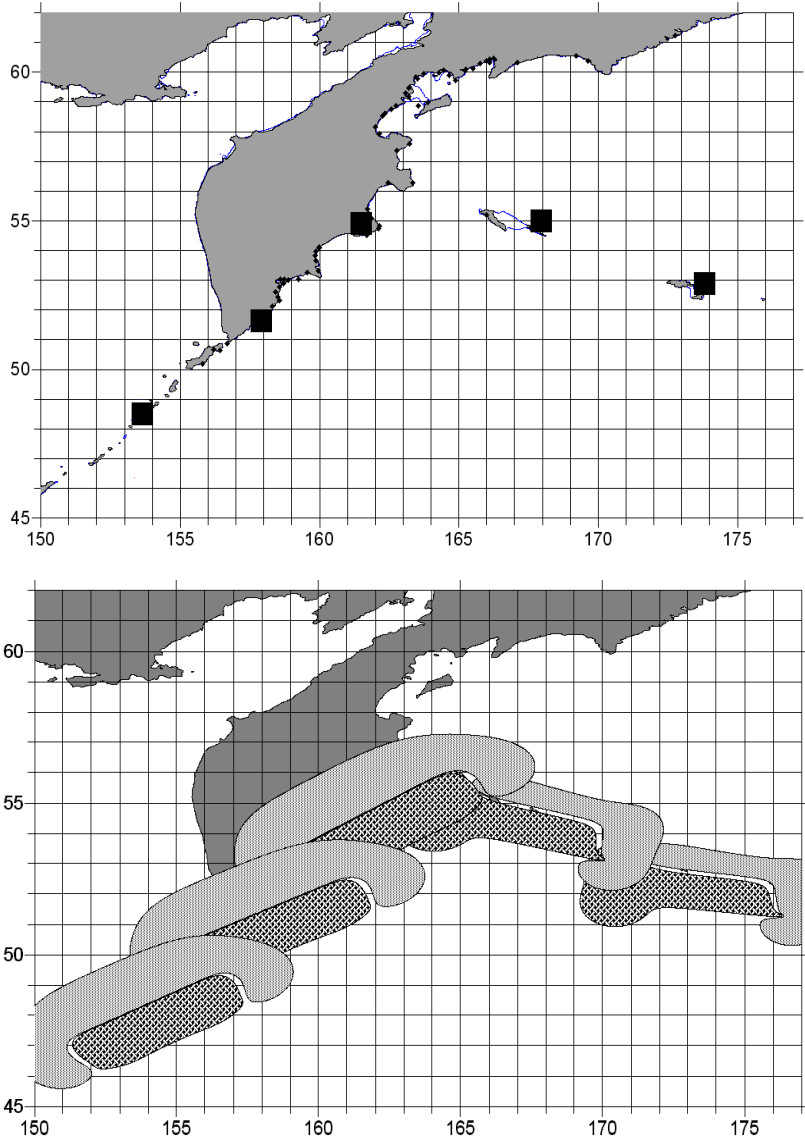


Fig. 9. Location of initial ocean surface disturbances in case of model sources with 9.0 magnitude

Long-term authors experience in solving fundamental and applied tsunami problems showed that classical equations of shallow water are enough to determine maximum wave heights in vicinity of protected points (up to 5-meter isobath). These equations are characterized by set of “physical”, “geographical” and “mathematical” parameters. Physiographic parameters include initial data

(initial free surface disturbance), boundary (structure and coastal) configuration, boundary conditions, bathymetry, bottom surface roughness, wind friction, turbulent exchange coefficients, etc. Mathematical parameters arise in the course of computational algorithm construction.

Computation module of the system implements algorithm of calculation of tsunami propagation with account of two types of boundary conditions – reflection at vertical impermeable boundary and water discharge to the outside of computational domain. The algorithm is based on a two-step MacCormack scheme [2,3].

Large size of computational domain required using geographical reference system wherein linear equations of shallow water with account of Coriolis force and bottom friction are of the following form:

$$\begin{aligned} \frac{\partial h}{\partial t} + \frac{1}{R \cos \varphi} \left[\frac{\partial(Hu)}{\partial \lambda} + \frac{\partial(Hv \cos \varphi)}{\partial \varphi} \right] &= 0, \\ \frac{\partial u}{\partial t} + \frac{g}{R \cos \varphi} \frac{\partial \eta}{\partial \lambda} &= f_1, \\ \frac{\partial v}{\partial t} + \frac{g}{R} \frac{\partial \eta}{\partial \varphi} &= f_2. \end{aligned} \tag{3}$$

Here R is the mean radius of the Earth, φ is latitude, λ is longitude, t is time, $h = H + \eta$ is the total depth, H is the depth of undisturbed water surface, η is the water surface elevation, g is the gravity acceleration, u and v are the velocity vector components in the line of λ and φ respectively, $f_1 = lv - gk^2 \frac{u\sqrt{u^2+v^2}}{h^{4/3}}$, $f_2 = -lu - gk^2 \frac{v\sqrt{u^2+v^2}}{h^{4/3}}$, $l = 2\omega \sin \varphi$, ω is the angular velocity of the Earth, k is the roughness coefficient.

Nonlinear equations of shallow water on a sphere can be written in the following form:

$$\begin{aligned} \frac{\partial h}{\partial t} + \frac{1}{R \cos \varphi} \left[\frac{\partial hu}{\partial \lambda} + \frac{\partial hv \cos \varphi}{\partial \varphi} \right] &= 0, \\ \frac{\partial u}{\partial t} + \frac{1}{R} \left[\frac{1}{2 \cos \varphi} \frac{\partial u^2}{\partial \lambda} + v \frac{\partial u}{\partial \varphi} + \frac{g}{\cos \varphi} \frac{\partial \eta}{\partial \lambda} \right] &= f_1, \\ \frac{\partial v}{\partial t} + \frac{1}{R} \left[\frac{u}{\cos \varphi} \frac{\partial v}{\partial \lambda} + \frac{1}{2} \frac{\partial v^2}{\partial \varphi} + g \frac{\partial \eta}{\partial \varphi} \right] &= f_2. \end{aligned} \tag{4}$$

Considering bounded domain $\Omega(\lambda, \varphi) = \{(\lambda, \varphi) : \lambda_1 \leq \lambda \leq \lambda_2, \varphi_1 \leq \varphi \leq \varphi_2\}$ in the plane of geographical coordinates φ and λ , introduce on it constant rectangular mesh

$$\overline{\Omega} = \{(\lambda_i, \varphi_j) : \lambda_1 \leq \lambda_i \leq \lambda_2, \varphi_1 \leq \varphi_j \leq \varphi_2, 0 \leq i \leq N_\lambda, 0 \leq j \leq N_\varphi\}$$

with steps $\Delta\lambda$ and $\Delta\varphi$ in the line of spatial variables λ and φ respectively. Let $\Delta\tau^n = t^{n+1} - t^n$ be as time step. In terms of mesh functions depending on discrete variables $\lambda_i, \varphi_j, t^n$, explicit two-step finite-difference scheme approximating linear model (3) in internal nodes of grid $\overline{\Omega}$ is of the following form:

Step 1

$$\begin{aligned} \frac{\hat{h}_{ij} - h_{ij}^n}{\tau^n} + \frac{1}{R \cos \varphi_j} \left[\frac{H_{ij}^n u_{ij}^n - H_{i-1j}^n u_{i-1j}^n}{\Delta\lambda} + \frac{\cos \varphi_j H_{ij}^n v_{ij}^n - \cos \varphi_{j-1} H_{ij-1}^n v_{ij-1}^n}{\Delta\varphi} \right] &= 0, \\ \frac{\hat{u}_{ij} - u_{ij}^n}{\tau^n} + \frac{g}{R \cos \varphi_j} \frac{\eta_{ij}^n - \eta_{i-1j}^n}{\Delta\lambda} &= f_{1ij}^n, \\ \frac{\hat{v}_{ij} - v_{ij}^n}{\tau^n} + \frac{g}{R} \frac{\eta_{ij}^n - \eta_{ij-1}^n}{\Delta\varphi} &= f_{2ij}^n, \end{aligned} \tag{5}$$

$$f_{1ij}^n = l_j v_{ij}^n - gk^2 \frac{u_{ij}^n \sqrt{(u_{ij}^n)^2 + (v_{ij}^n)^2}}{(h_{ij}^n)^{4/3}}, \quad f_{2ij}^n = -l_j u_{ij}^n - gk^2 \frac{v_{ij}^n \sqrt{(u_{ij}^n)^2 + (v_{ij}^n)^2}}{(h_{ij}^n)^{4/3}}, \quad l_j = 2\omega \sin \varphi_j.$$

Step 2

$$\begin{aligned} & \frac{h_{ij}^{n+1} - (h_{ij}^n + \hat{h}_{ij})/2}{\tau^n/2} + \\ & + \frac{1}{R \cos \varphi_j} \left[\frac{H_{i+1j}^n \hat{u}_{i+1j} - H_{ij}^n \hat{u}_{ij}}{\Delta \lambda} + \frac{\cos \varphi_{j+1} H_{ij+1}^n \hat{v}_{ij+1} - \cos \varphi_j H_{ij}^n \hat{v}_{ij}}{\Delta \varphi} \right] = 0, \\ & \frac{u_{ij}^{n+1} - (u_{ij}^n + \hat{u}_{ij})/2}{\tau^n/2} + \frac{g}{R \cos \varphi_j} \frac{\hat{h}_{i+1j} - H_{i+1j}^n - \hat{h}_{ij} + H_{ij}^n}{\Delta \lambda} = \hat{f}_{1ij}, \\ & \frac{v_{ij}^{n+1} - (v_{ij}^n + \hat{v}_{ij})/2}{\tau^n/2} + \frac{g}{R} \frac{\hat{h}_{ij+1} - H_{ij+1}^n - \hat{h}_{ij} + H_{ij}^n}{\Delta \varphi} = \hat{f}_{2ij}, \end{aligned} \quad (6)$$

$$\hat{f}_{1ij} = l_j \hat{v}_{ij} - gk^2 \frac{\hat{u}_{ij} \sqrt{(\hat{u}_{ij})^2 + (\hat{v}_{ij})^2}}{(\hat{h}_{ij})^{4/3}}, \quad \hat{f}_{2ij} = -l_j \hat{u}_{ij} - gk^2 \frac{\hat{v}_{ij} \sqrt{(\hat{u}_{ij})^2 + (\hat{v}_{ij})^2}}{(\hat{h}_{ij})^{4/3}}.$$

For a system of nonlinear equations a similar algorithm is built:

Step 1

$$\begin{aligned} & \frac{\hat{h}_{ij} - h_{ij}^n}{\tau^n} + \frac{1}{R \cos \varphi_j} \left[\frac{h_{ij}^n u_{ij}^n - h_{i-1j}^n u_{i-1j}^n}{\Delta \lambda} + \frac{\cos \varphi_j h_{ij}^n v_{ij}^n - \cos \varphi_{j-1} h_{ij-1}^n v_{ij-1}^n}{\Delta \varphi} \right] = 0, \\ & \frac{\hat{u}_{ij} - u_{ij}^n}{\tau^n} + \frac{1}{R \cos \varphi_j} \left[\frac{(u_{ij}^n)^2 - (u_{i-1j}^n)^2}{2\Delta \lambda} + g \frac{\eta_{ij}^n - \eta_{i-1j}^n}{\Delta \lambda} \right] + \frac{v_{ij}^n}{R} \frac{u_{ij}^n - u_{i-1j}^n}{\Delta \varphi} = f_{1ij}^n, \\ & \frac{\hat{v}_{ij} - v_{ij}^n}{\tau^n} + \frac{u_{ij}^n}{R \cos \varphi_j} \frac{v_{ij}^n - v_{i-1j}^n}{\Delta \lambda} + \frac{1}{R} \left[\frac{(v_{ij}^n)^2 - (v_{ij-1}^n)^2}{2\Delta \varphi} + g \frac{\eta_{ij}^n - \eta_{ij-1}^n}{\Delta \varphi} \right] = f_{2ij}^n. \end{aligned}$$

Step 2

$$\begin{aligned} & \frac{h_{ij}^{n+1} - (h_{ij}^n + \hat{h}_{ij})/2}{\tau^n/2} + \\ & + \frac{1}{R \cos \varphi_j} \left[\frac{\hat{h}_{i+1j} \hat{u}_{i+1j} - \hat{h}_{ij} \hat{u}_{ij}}{\Delta \lambda} + \frac{\cos \varphi_{j+1} \hat{h}_{ij+1} \hat{v}_{ij+1} - \cos \varphi_j \hat{h}_{ij} \hat{v}_{ij}}{\Delta \varphi} \right] = 0, \\ & \frac{u_{ij}^{n+1} - (u_{ij}^n + \hat{u}_{ij})/2}{\tau^n/2} + \\ & + \frac{1}{R \cos \varphi_j} \left[\frac{(\hat{u}_{i+1j})^2 - (\hat{u}_{ij})^2}{2\Delta \lambda} + g \frac{\hat{h}_{i+1j} - H_{i+1j}^n - \hat{h}_{ij} + H_{ij}^n}{\Delta \lambda} \right] + \frac{\hat{v}_{ij}}{R} \frac{\hat{u}_{ij+1} - \hat{u}_{ij}}{\Delta \varphi} = \hat{f}_{1ij}, \\ & \frac{v_{ij}^{n+1} - (v_{ij}^n + \hat{v}_{ij})/2}{\tau^n/2} + \\ & + \frac{\hat{u}_{ij}}{R \cos \varphi_j} \frac{\hat{v}_{i+1j} - \hat{v}_{ij}}{\Delta \lambda} + \frac{1}{R} \left[\frac{(\hat{v}_{ij+1})^2 - (\hat{v}_{ij})^2}{2\Delta \varphi} + g \frac{\hat{h}_{ij+1} - H_{ij+1}^n - \hat{h}_{ij} + H_{ij}^n}{\Delta \varphi} \right] = \hat{f}_{2ij}. \end{aligned}$$

Top and bottom boundaries of the computational domain are parallel to equator and left and right ones go along meridians. Parts of “vertical wall” boundary go through nodes of constant rectangular mesh in such a way that they are always parallel to exterior of rectangular $\Omega(\lambda, \varphi)$. On the side boundaries boundary condition is given by $u = 0$, $\partial v / \partial \lambda = 0$, $\partial \eta / \partial \lambda = 0$ on meridians and $v = 0$, $\partial u / \partial \varphi = 0$, $\partial \eta / \partial \varphi = 0$ on parallels. On exterior “open” boundaries the conditions of free passage – Sommerfeld conditions – are postulated. In coordinates in use they are given on parallels by

$$R \frac{\partial \eta}{\partial t} \pm c \frac{\partial \eta}{\partial \varphi} = 0, \quad R \frac{\partial u}{\partial t} \pm c \frac{\partial u}{\partial \varphi} = 0, \quad R \frac{\partial v}{\partial t} \pm c \frac{\partial v}{\partial \varphi} = 0,$$

and on meridians

$$R \frac{\partial \eta}{\partial t} \pm \frac{c}{\cos \varphi} \frac{\partial \eta}{\partial \lambda} = 0, \quad R \frac{\partial u}{\partial t} \pm \frac{c}{\cos \varphi} \frac{\partial u}{\partial \lambda} = 0, \quad R \frac{\partial v}{\partial t} \pm \frac{c}{\cos \varphi} \frac{\partial v}{\partial \lambda} = 0,$$

where $c = \sqrt{gh}$ is wave propagation velocity and selection of mark depends on direction of external normal to the corresponding boundary.

Bottom bathymetry and land topography are fixed, are keeping in the corresponding data base and are using by computational and rendering modules. This data represents grid function $\bar{H}(\lambda_i, \varphi_j)$, $0 \leq i \leq N_\lambda$, $0 \leq j \leq N_\varphi$, defined at nodes of discrete domain $\bar{\Omega}$, and it is defined as depth and height values given on constant 1-minute grid.

Initial free surface disturbance is calculated by special computational module; initial velocities are set as zero. Time step of the grid is calculated on every step from stability condition. Algorithm allows solution smoothing through certain number of steps. Parameters of this smoothing are set in special file.

The first version of user-operate mode software has following functionalities: review of maximum and minimum amplitudes distribution and wave heights in given protected point for all tsunamigenic earthquakes, and review of maximum and minimum amplitudes distribution and wave heights for given tsunamigenic earthquake in all protected point. Export of these distributions to text files is possible. In view mode for given protected point and given earthquake it is possible to draw corresponding marigram.

7 Database Structure

In the present article “data base” means set of tables (SQL-bases) and folders on a disk. Microsoft Access was chosen as the data management system, as it is well documented and meets the requirements of data access speed. This system is easy-to-work and supports SQL language that will allow to change SQL database easily in the future.

The storage structure suggested and realized by the authors allows to store database information about model tsunamigenic earthquakes, protected points and other entities. Big volume data (marigrams, arrays of free surface disturbances, etc.) are stored at local disk. It allows to gain access to information using other “external” software tools. Using standard database management system provides appropriate speed of access to storing information by SQL queries.

As mentioned above, the database includes set of database tables and local storages (folders). The table `dt_defended_points` contains the set of protected points characteristics, `dt_points` contains features of all tide-gages with its coordinates, `dt_sources` contains features of model tsunamigenic earthquakes with descriptions and references to calculated arrays of corresponding values of ocean surface disturbances, `dt_calc_params` contains parameters of computational algorithms. Development and filling of this table is not finished yet; new fields will be added to the table. The table `dt_mareos` contains a list of references to calculated marigrams. Finally, the table `dt_maxmin_val` contains characteristics of tsunami events at protected points. Its content regenerates after each calculation.

8 Structure of Project's Folders

In the present article “project” means a set of serial calculations with given computational domain, protected points, model tsunamigenic earthquakes, mathematical model and computational algorithms.

In the project's root folder there are:

The **“Bathymetry”** folder with bathymetry of computational domain. This folder contains file Bathymetry.grd in binary format .grd (format of Surfer system). Folder **“Database”** contains project's database, file of general database (supporting SQL language and construction of several tables, MS Access in the present version) main_db.mdb contains data about calculations, its parameters, etc. Folder **“Import”** is meant for the import of data calculated by console utility serial_calc to the database main_db.mdb. Before import the following files and folders should be put in: folder **“Input”** with files mareographs.txt and sources.txt taken from utility folder serial_calc, folder **“Calculation”** with files xxx_MareogramsAddCalcul.dat. The folder **“Export”** is meant for export of data from main_db.mdb in format of other programs. Subfolders with names formed from of the current date are created in this folder. **“Maxmin definded points”** contains maximum and minimum distributions for every protected point. **“Maxmin sources”** contains maximum and minimum distributions for every model earthquake.

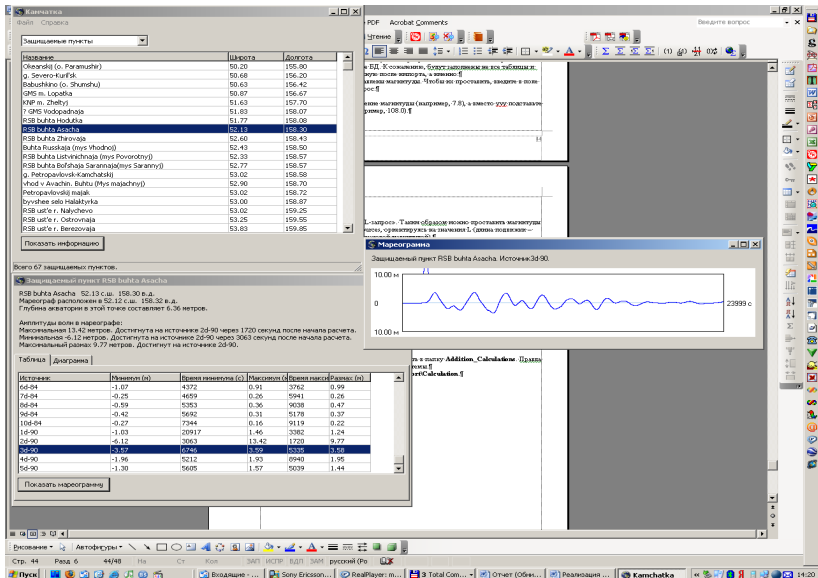


Fig. 10. Window of access to information about tsunami events at the protected point and corresponding marigram

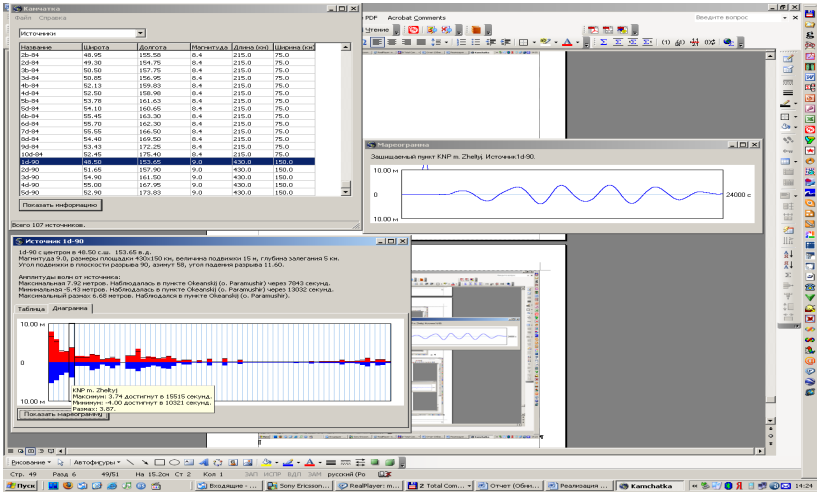


Fig. 11. Window of access to information about tsunami event, generated by given model tsunamigenic earthquake at the protected point, corresponding marigrams (at the right), distribution of tsunami event characteristics (at the bottom), information about numeric values of given earthquake at given protected point (in the context window)

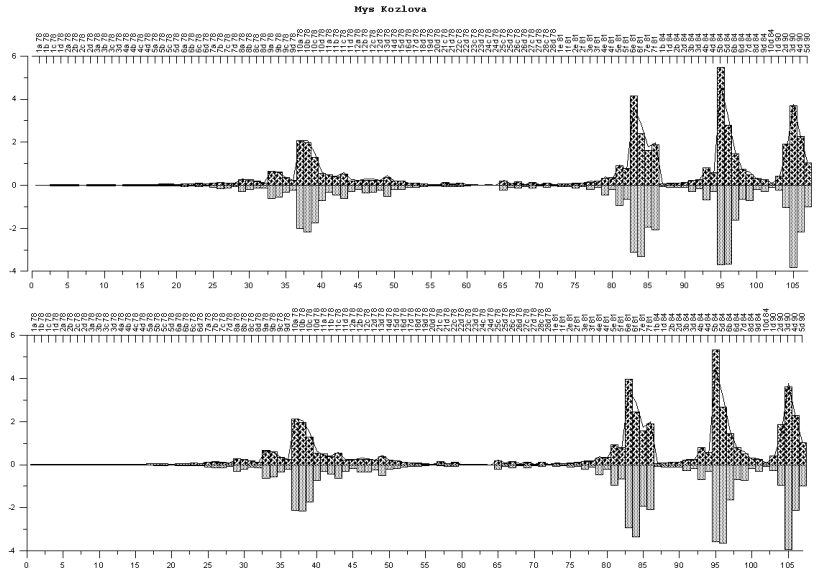


Fig. 12. Example of distribution of tsunami event characteristics at the protected point for all earthquakes. Top plot corresponds to results of linear model of shallow water, and bottom one corresponds to nonlinear model.

Folder “**Modules**” contains project’s module files. For instance, it will contain modules for serial calculations. Folder “**Sources**” contains ocean surface disturbances calculated for model tsunamigenic earthquakes. It contains files in binary format grd: xxx_z.grd (array of local disturbances in rectangular coordinates) and xxx_etta.grd (array of disturbances in whole domain in spherical coordinates), where xxx is code name of source. Folder “**Mareograms**” stores files xxx_mareograms.dat (marigrams).

9 Examples of Results Presentation

The following series of figures represents the sequence of work widows arising at different stages of user-operating mode.

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