Technique of near-field probabilistic tsunami zoning applied to the Bechevinskaya Cove (the Kamchatka Peninsula)

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Abstract

Currently, the most popular approach for assessing the tsunami hazard on a coast is the PTHA (Probabilistic Tsunami Hazard Assessment). In this study, we develop one of the variants of the SPTHA (Seismic PTHA) method, adapted to solving near-field tsunami zoning problems. The approach is applied to assessing the tsunami hazard of the Bechevinskaya Cove located on the eastern coast of the Kamchatka Peninsula in the northern part of Avachinsky Bay. We propose the method, algorithms and results of probabilistic assessment of the cove's tsunami hazard in order to determine the safest water areas, in which the values of the intensity measures (IMs) of tsunami will not exceed the specified threshold values with the given recurrence rates. The method includes analysis of seismotectonics of the region, construction of a catalog of model tsunamigenic earthquakes, determination of their statistical characteristics, scenario numerical modeling of the dynamics of tsunami waves, calculations of the values of IMs that can be exceeded with the given recurrence rates (on average 1 time in 100, 500, 1000 years). Spatial distributions of the maximum wave heights and maximum velocities are provided for the recurrence rates. Three configurations of the water area are considered, including the possibility of constructing protective structures, and conclusions are drawn about their influence on the tsunami hazard assessments in the cove. 1. Introduction The problem of tsunami zoning, which consists in the quantitative classification of the coast and adjacent aquatory by the degree of tsunami hazard, is one of the classic tsunami problems and requires the use of multidisciplinary tools and methods for its solution (Gusiakov, 2017). Hereinafter, tsunami hazard is the degree (level) of exposure of water areas and coasts to the tsunami threat in terms of measuring the catastrophic wave intensity. One of the first approaches to solving the problem of tsunami zoning was a method based on the use of historical data, materials from modern instrumental observations, as well as geological studies of paleo-tsunami along the coastal areas. The main limitation of the "historical" approach is a short series of observations. For near-field tsunami zoning problems the number of such observations is usually objectively limited by the short historical period of observations and the preservation of tsunami deposits, which also limits the accuracy of statistical estimates of tsunami hazard. Scenario modeling is an alternative based on estimates of the statistical properties of tsunami sources and the results of simulation (mathematical modeling) of the transformation of tsunami waves from the source to the coast. This approach uses a series of model tsunamigenic events of arbitrary length and thus clarifies probabilistic estimates of tsunami hazard. One of the ways to use the results of scenario calculations to solve the problem of tsunami zoning is to determine the extreme (worst case)

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Abstract

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1. Introduction

The problem of tsunami zoning, which consists in the quantitative classification of the coast and adjacent aquatory by the degree of tsunami hazard, is one of the classic tsunami problems and requires the use of multidisciplinary tools and methods for its solution (Gusiakov, 2017). Hereinafter, tsunami hazard is the degree (level) of exposure of water areas and coasts to the tsunami threat in terms of measuring the catastrophic wave intensity. One of the first approaches to solving the problem of tsunami zoning was a method based on the use of historical data, materials from modern instrumental observations, as well as geological studies of paleo-tsunami along the coastal areas. The main limitation of the "historical" approach is a short series of observations. For near-field tsunami zoning problems the number of such observations is usually objectively limited by the short historical period of observations and the preservation of tsunami deposits, which also limits the accuracy of statistical estimates of tsunami hazard. Scenario modeling is an alternative based on estimates of the statistical properties of tsunami sources and the results of simulation (mathematical modeling) of the transformation of tsunami waves from the source to the coast. This approach uses a series of model tsunamigenic events of arbitrary length and thus clarifies probabilistic estimates of tsunami hazard.

One of the ways to use the results of scenario calculations to solve the problem of tsunami zoning is to determine the extreme (worst case) characteristics of the tsunami wave impact on the coast and coastal facilities. Development of mathematical modeling methods of wave hydrodynamics, a significant increase in available computing resources and means of implementing numerical algorithms made it possible to proceed to the implementation of the PTHA (Probabilistic Tsunami Hazard Assessment) methodology, which is close to probabilistic seismic hazard analysis (e.g. Castaños and Lomnitz, 2002, Mulargia *et al*., 2017). Detailed reviews on the theoretical aspects of the PTHA technique and its practical application can be found in recent publications (Grezio et al., 2017; Park et al. 2018; Løvholt et al., 2019). PTHA for the Russian coasts was carried out, in particular, by Gusiakov et al. (2019) – to assess the tsunami hazard of the coasts of the Kuril-

Kamchatka region, the Japan, Okhotsk and Black seas and to build relevant overview maps; and by Kulikov et al. (2016) - to assess the tsunami hazard of the Arctic coast.

Tsunami waves can be generated by various natural extreme events: earthquakes, volcanic eruptions, landslides, avalanches, and meteorological phenomena. In this paper, we estimate tsunami hazard on an area located on the eastern coast of the Kamchatka Peninsula, so we consider exclusively seismogenic tsunamis, which account for about 90% of the events that occurred off the Far Eastern coast of Russia (Gusiakov, 2016). The term SPTHA (Seismic PTHA) is proposed for this class of problems (Lorito, 2015). Scenario modeling of the SPTHA requires preliminary construction of regional empirical distributions of each seismic intensity parameters, based on which a synthetic earthquake catalog is created that has statistical properties similar to those of regional seismic intensity and reproduces the characteristic features of local earthquake sources. The sources from this catalog serve as input data for scenario modeling of tsunami wave propagation and its interaction with the coast. It is assumed that the statistical properties of characteristics of the manifestation of tsunami waves generated by earthquakes from this catalog will also correspond to reality.

Building a set of model seismic events can be performed in various ways. For example, by creating sources with fixed parameter values determined with the assistance of experts in the field of regional seismotectonics. Gusiakov et al. (2019) used this approach to assess the tsunami hazard of the Kuril-Kamchatka region, the Japanese, Okhotsk and Black seas and building review maps showing the long-coast distribution of tsunami characteristics that can be exceeded with a given probability within a given period. Another option is to use stochastic methods for determining parameter values that meet the distributions set by an expert.

Following the SPTHA technique, after constructing a set of model sources of tsunamigenic earthquakes, numerous scenario calculations are performed, the recurrence rate of the sources is determined from catalogs of historical and instrumental data, as well as using one or another interpretation of the Gutenberg-Richter relationship, then the recurrence rate of seismic events is converted into the recurrence rate of the tsunami intensity measure (IM), and finally, the results are presented in a form that meets the requirements of interested persons and organizations. Hereinafter, the recurrence rate refers to the average number of events of the corresponding model of the Poisson process per unit of time.

The tasks of assessment of tsunami hazard are usually divided by scale. Gusiakov (2017) determined three main levels: near-field (local) (map scale 1:2,000-1:10,000), aimed at providing data for design and construction in a tsunami hazardous coastal zone; regional (1:500,000-1:4,000,000), designed to identify areas that require detailed tsunami zoning; and global (1:10,000,000 and smaller), providing a compact presentation of information on the relative tsunami hazard of various regions of the oceans. For problems of each scale, the corresponding versions of the general methodology are built up, which may differ by IMs, by input data, and by mathematical models and algorithms. For example, the IM in problems of global and regional scales can be wave amplitudes (the maximum modulo positive and negative values of the displacement of water surface relative to the undisturbed level), the maximum wave heights – the sum of values of maximum positive and negative amplitudes, the maximum wave flow velocities, some integral values (over time, along a coastline, etc.). Solving local-scale problems usually involve modeling of the final phase of the tsunami wave transformation – its run-up on the coast and interaction with coastal structures. Therefore, it is reasonable to consider additional IMs, such as the maximum height and length of the splash range, the maximum inundation depth, the landflood duration. Park and Cox (2016) and Løvholt et al. (2019) also proposed to use the momentum flux (wave flow impulse) calculated as the product of the total depth of the water layer by the square of its flow velocity.

In this study, we assess the tsunami hazard of the Bechevinskaya Cove located on the eastern coast of the Kamchatka Peninsula in the northern part of Avachinsky Bay, using the proposed SPTHA technique adapted to the solution of local tsunami zoning. The peculiarity of the problem is to identify the least dangerous water areas of the cove, in which the values of IMs of tsunami will not exceed the given threshold values with the given recurrence intervals (100, 500, 1000 year). At the same time, various configurations of the water area are considered, including the possibility of constructing protective structures, and conclusions are drawn about their influence on the tsunami hazard assessments in the cove.

2. Research area.

The Bechevinskaya Cove is located in the northern part of Avachinsky Bay in the east of the Kamchatka Peninsula (Fig. 1). The narrow cove (up to 2 km wide) extends for about 10 km to the northeastern direction within the mountainous Shipunsky Peninsula. The peculiarity of the cove bathymetry is shallow water with depths of up to several meters at the entrance (about half of the cove) and deep water (with depths of up to 50 m) at the top part of the cove. The Bechevinskaya Cove was formed as a glacial fjord, and the shallow part is the moraine deposits, submerged due to the sea level rise in the Holocene.

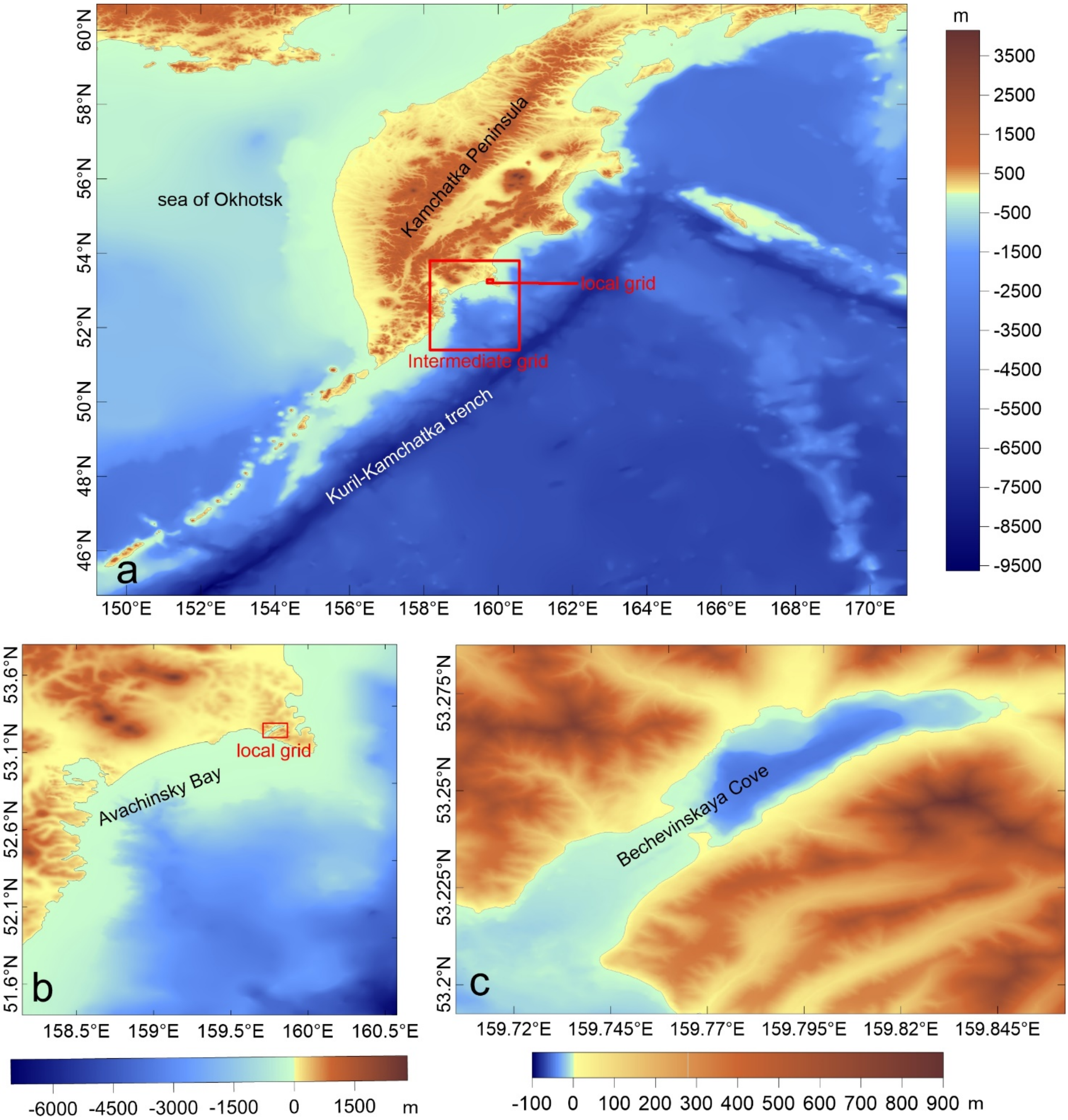

Fig. 1. Numerical model bathymetry and grid maps for (a) global, (b) intermediate and (c) local grids.

In the modern tectonic understanding, the study area is located in the hanging wing of the Kamchatka subduction zone. As a result, it belongs to the most seismically active regions of the Kamchatka Peninsula (and the world), where the strongest earthquakes with magnitudes $M_W \sim 9$ are known. The Bechevinskaya Cove is located about 160 km far from the Kuril–Kamchatka deep-water trench. The hypocenters of most earthquakes in this area are located at a depth of 60-90 km. Most of the regional tsunamigenic earthquakes occur in the strip parallel to the trench (Gusiakov, 2016).

3. A synthetic catalog simulating seismicity off the eastern coast of the Kamchatka Peninsula.

The constructed catalog of model tsunamigenic earthquakes contains the information used as an input in the scenario modeling of tsunami waves. It consists of lines corresponding to a single seismic event and containing information on its source, which is necessary for calculating the sea bed deformation caused by it and, as a result, the disturbance of the ocean surface that generates a tsunami wave. It is assumed that the source dislocations are flat and rectangular, and the corresponding displacement is uniformly distributed over the rupture surface. The set of parameters of such a tsunamigenic earthquake model are centroid coordinates (latitude, longitude, depth), the source mechanism (strike, dip, rake) and the size (length and width), the slip value and the event magnitude. The large amount of computing resources required for numerous scenario modeling of tsunami waves limits the allowed size of the synthetic catalog. Taking into account the location of the studied water area relative to the adjacent seismic zone and its size, the final version of the catalog contained 198 model earthquakes.

All earthquake parameters in the catalog are generated as pseudo-random values corresponding to the specified distributions. The seismic process is assumed to be stationary; that is, the distributions used do not depend on time. Cartographic constructions are carried out in a specially selected oblique cylindrical and approximately equal-area projection, in which the axis of the Kuril–Kamchatka trench is close to a straight line (Fig. 2). In this projection, parameter distributions have the simplest form.

The parameters of model earthquakes can be divided into two groups based on statistical properties. The first group includes the coordinates, mechanisms, and magnitude of earthquakes that have accumulated significant observational data. The second group consists of source sizes and slip values, for which there are few real estimates for the Kamchatka region. The values of these parameters are determined by the given functions of one generated random variable – the magnitude. For this, we use the empirical dependencies of the length L_S and width W_S of the rupture surface (in kilometers), as well as the slip value D_S (in meters), proposed in the study of Papazachos et al. (2004) for subduction earthquakes with magnitudes M_W up to 9.2:

$$\log(L_S) = 0.55 \cdot M_W - 2.19,\ \log(W_S) = 0.31 \cdot M_W - 0.63,\ \log(D_S) = 0.64 \cdot M_W - 4.78 \qquad (1)$$

The remaining source parameters (including the magnitude) are considered as independent random variables.

Constructing the regional empirical distributions, we use earthquake catalogs generally covering the observation period from the beginning of the 20th century to June 2018 (ISC (ftp://ftp.isc.ac.uk/pub/isf/catalogue/), earthquakes catalogue for the Kamchatka Peninsula and the Commander Islands (http://sdis.emsd.ru/main.php/)), and GCMT (https://www.globalcmt.org/CMTsearch.html) for seismic moment tensors. The ISC-GEM catalog (Storchak et al., 2013; 2015; Di Giacomo *et al*., 2018) and the results of studies of historical and paleo-tsunami deposits on the coast of Avachinsky Bay of the Kamchatka Peninsula (Pinegina and Bazanova, 2016; Pinegina et al., 2018) are also used to evaluate the law of magnitude recurrence rate.

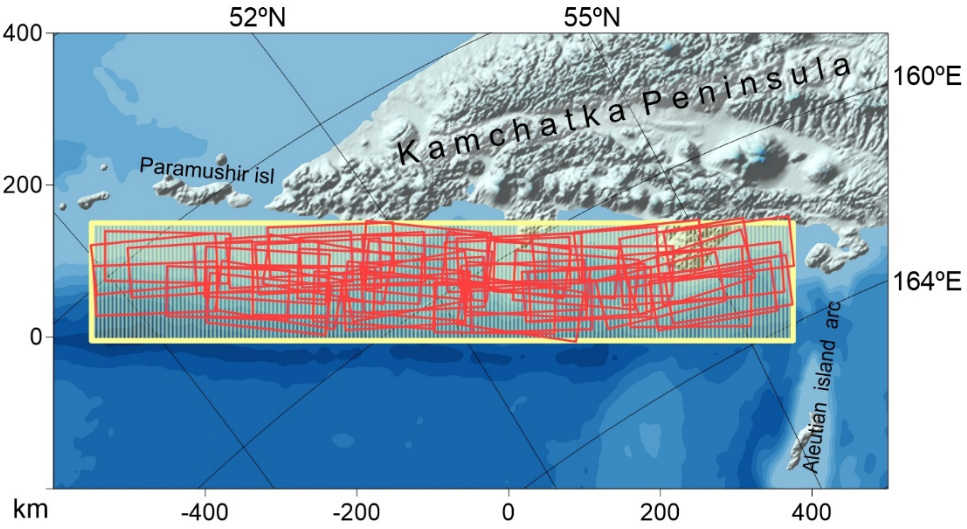

Fig. 2. Example of a created synthetic catalog of tsunamigenic earthquakes for the eastern coast of the Kamchatka Peninsula. The yellow rectangle is the geographic area for which the catalog is being built. The red rectangles are projections onto the free surface of model sources generated with magnitudes 7.5-9.0

In the final form, the empirical distributions used have a simple parametric form. However, to select an adequate distribution model for each parameter, a preliminary study of its changes in space was carried out. In some cases, this revealed spatial trends that were included in the distributions (see the example in Fig. 3). In addition, the distributions are affected by the spatial constraint that prevent the source areas from significantly extending beyond the accepted region of the possible occurrence of tsunamigenic earthquakes.

In the selected cartographic projection, the area occupied by the epicenters of potentially tsunamigenic (and dangerous for the Bechevinskaya Cove) near-field earthquakes is well approximated by a rectangle (Fig. 2). Real weak earthquakes are distributed irregularly in this area, and the available event statistics for strong events are not sufficient to highlight the most dangerous zones. Also, the sizes of the strongest known events are comparable to the entire selected area. Therefore, a uniform distribution of epicenters is used in a random sampling of model events. At the same time, the constraint mentioned above on the location of source sites is taken into account (inconsistent events are skipped). Since a relatively small set of model earthquakes (198 events) is used in scenario modeling, we utilize the Mitchell algorithm to improve the uniformity of their location in space (Mitchell, 1991).

The empirical distributions of the earthquake mechanism parameters and the centroid depth were constructed according to the common scheme. Initially, we assume that the density function ρ of a certain parameter α could be represented as

$$\rho = \rho\left(\alpha - T_\alpha\left(X\right)\right), \tag{2}$$

where $T_\alpha\left(X\right)$ is the smooth trend of the parameter α, and the function shape ρ does not depend on the argument X, which for distributions of the mechanism parameters is a coordinate along the Kuril–Kamchatka trench (trend along the strike of the subduction zone), and for the centroid depth – the distance from the trench. Last assumption corresponds to a constant angle δ of the seismic source zone (the dip angle is taken equal to 22°). Fig. 3 illustrates the construction of such a distribution for one of the parameters of the mechanism λ – the rake angle.

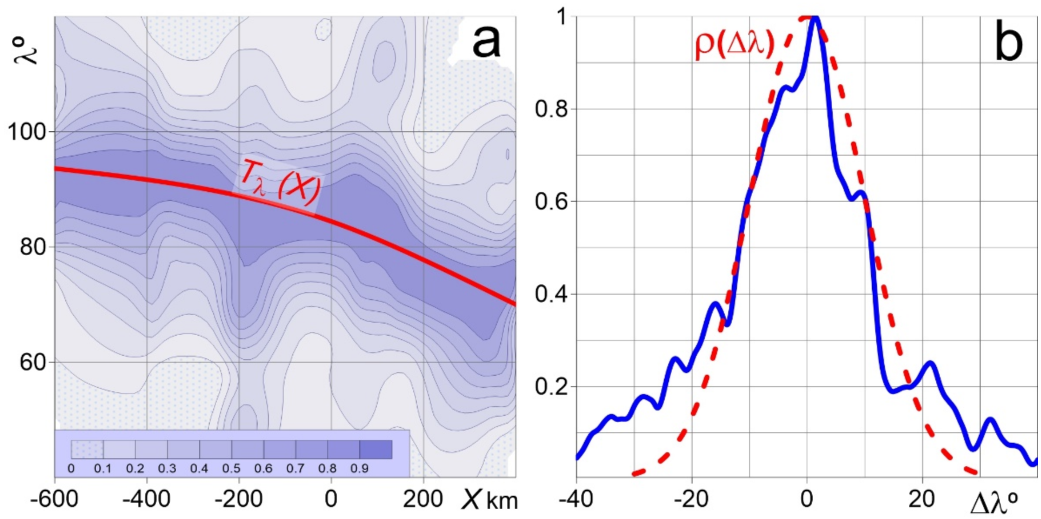

Fig. 3. Example of constructing a distribution for generating the rake angle in the mechanism of a model source. (a) - a smoothed two-dimensional density of real events, which demonstrates the change in the distribution of parameter λ along the strike of the subduction zone (X coordinate). The solid line corresponds to the calculated trend of the average value of empirical density. In a two-dimensional density map, each section parallel to the λ-axis is normalized to its maximum. (b) - a smoothed density (solid line) of deviations of real values from the trend: $\Delta\lambda\left(X\right) = \lambda\left(X\right) - \lambda_{trend}\left(X\right)$ and (dashed line) empirical Gaussian density (normalized to maximum), approximating the dashed line. The standard deviation is taken equal to 10°.

Preliminary studies have shown that the angle λ in the study area has a steady tendency to change along the strike of the subduction zone. Therefore, the parametric trend of this change was evaluated in the first step. By smoothing, a two-dimensional density of a set of points (X, λ) corresponding to real earthquakes from the GCMT catalog is calculated, where X is the centroid coordinate along the trench, and λ is the rake in the mechanism of the same event (Fig. 3a). An approximating cubic spline $\lambda_{trend}\left(X\right)$ was drawn at the points of partial maxima, which is taken as the trend function $T_\alpha\left(X\right)$ included in (2).

In the second step (Fig. 3b), an independent of argument X function shape ρ_λ for parameter λ in (2) is estimated for the entire region. To do this, the values $\Delta\lambda\left(X\right) = \lambda\left(X\right) - \lambda_{trend}\left(X\right)$ for all X (all earthquakes and its mechanisms) are combined into a single set, using which the empirical distribution density of $\Delta\lambda$ is constructed (the dotted curve in Fig. Fig. 3b). Next, a Gaussian function is selected (the solid curve in Fig. Fig. 3b) that approximates the resulting density and is taken as an estimate $\rho_{\lambda}(\Delta\lambda)$ in (2).

When constructing a synthetic catalog, random epicenters are first generated, and their coordinates X^{p} are calculated (generated random variables are marked with an upper index). Then, for each event, a random value $\Delta\lambda^{p}$ is independently generated according to the density ρ_{λ}. Finally, a random parameter of the mechanism $\lambda^{p}(X^{p}) = \lambda_{trend}(X^{p}) + \Delta\lambda^{p}(X^{p})$ is calculated for each synthetic earthquake.

Distribution densities for the strike of rupture plane and the centroid depth D_0 of a synthetic event are constructed in a similar way. The dip angle δ for all rupture planes is assumed to be the same and equal to 22° – the slope of the upper part of the Kamchatka seismic source zone.

In real catalogs, earthquake magnitudes are distributed non uniformly. The recurrence rate of relatively weak events that do not generate significant tsunamis significantly exceeds the recurrence rate of the strongest earthquakes which are the most important for tsunami zoning. Therefore, using a synthetic catalog that simulates a real set of events in the problem under discussion is very inefficient. Instead, one can create a new catalog, consisting mainly of tsunamigenic events and specify their recurrence rates later analytically. In this paper, the entire interval of generated magnitudes ($M_W \in \Delta M \equiv [7.8,\ 9.0]$) was divided into subintervals ($\delta M = 0.2$), each included an equal number of random events. Thus, the equal magnitude representation is provided in the synthetic catalog.

The model probability frequency distribution $p_M(M_W)$ (earthquake magnitude recurrence rate graph) used below is constructed initially by smoothing the data from the catalogs mentioned above. Then the recurrence rate chart for the strongest events is corrected based on the data of paleo-earthquakes in Avachinsky Bay (Pinegina et al., 2018).

The presented methodology for creating a synthetic catalog of sources of near-field tsunamigenic earthquakes for the eastern coast of the Kamchatka Peninsula is implemented in a computer program which allows to generate random catalogs of arbitrary length and with a variety sets of events that follow the distributions described above. An example of a map constructed using this code is shown in Fig. 2. For clarity, it shows sources from the catalog of 50 events, less than in the catalog used in this work.

4. Methodology of scenario modeling.

As mentioned above, to calculate the IM of tsunami waves $I(Q,x,y)$ generated at a point with coordinates (x,y) by an earthquake with a set of parameters Q (in the Gusiakov-Okada model), a series of scenario simulations of all phases of tsunami wave transformation were performed. We used three nested grids (Fig. 1) for its implementation. A detailed description of the nesting methods used and their verification are described in (Beisel et al., 2014, Gusev and Chubarov, 2018). In the "global" grid with the angular resolution of 30 seconds (about 925 m), the wave generation by a seismic event was calculated. The bathymetry for this grid was obtained from the GEBCO-2009 digital array – General Bathymetric Chart of the Oceans (https://www.gebco.net/ (Hall, 2006)) with the angular resolution of 1 minute, using piecewise bilinear interpolation. In the "intermediate" grid (with angular resolution of 5 seconds, about 154 m), the wave approach to the entrance to the cove was simulated. The bathymetry of this grid was obtained by digitizing the navigation map. Finally, in the "local" grid (with angular resolution of 0.5 seconds, about 15 m), the characteristics of the wave manifestation in the cove and its run-up on the shore were calculated. In this case, the bathymetry was also obtained by digitizing the navigation map, and the land relief model was obtained using data from the ArcticDEM arrays (https://www.pgc.umn.edu/data/arcticdem/) (Morin et al., 2016) and SRTM (http://www2.jpl.nasa.gov/srtm/).

The calculations were made for three layout configurations of the cove water area: taking into account the channel deepened for the passage of ships in the shallow part of the cove; taking into account the channel and the wave protection structure in the narrow part of the cove; taking into account the channel and the wave protection structure at the entrance to the cove (Fig. 4).

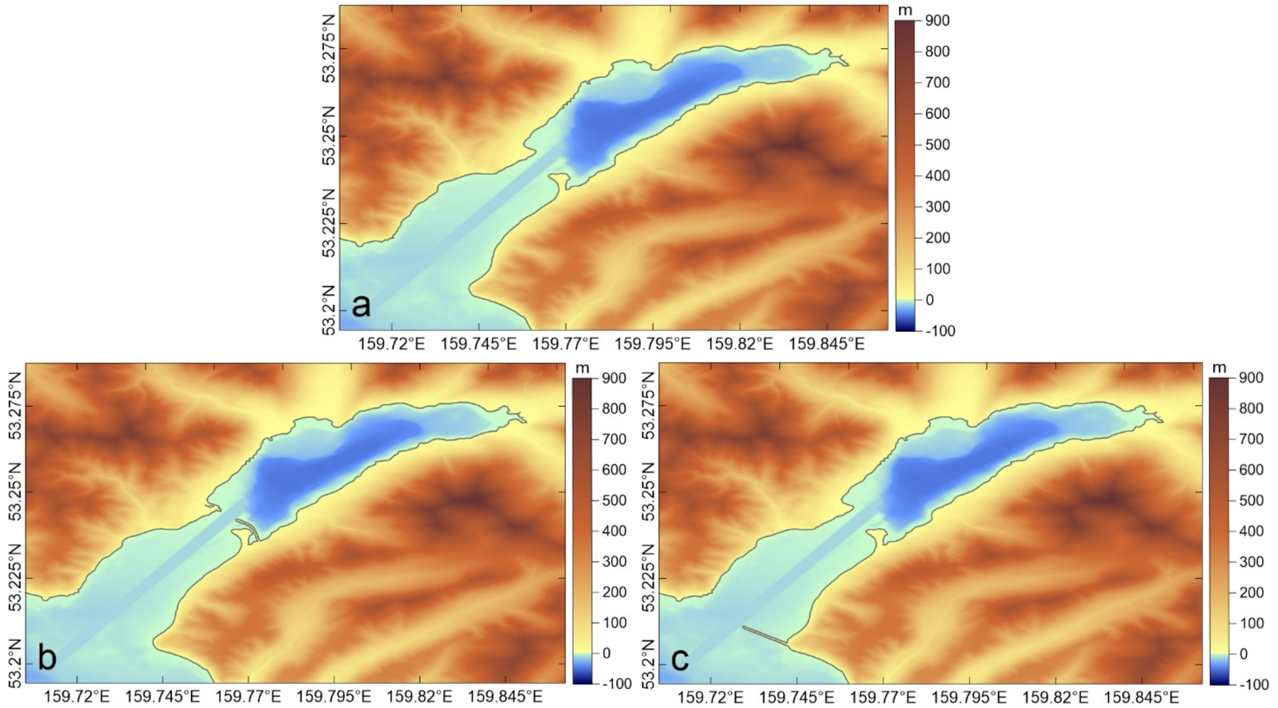

Fig. 4. Local grid map with a channel (*a*) and protective structures: (*b*) – in the narrow part of the cove, (*c*) – at the entrance to the cove

We placed 119 virtual gauges in the water area of the cove with a concentration near the considered protective structures to capture the characteristics of the wave regimes at each time step of the algorithm.

The generally accepted "piston" model of a seismic source was used (Gusiakov 1978, Okada 1985) to calculate the initial elevation of the free surface caused by a tsunamigenic earthquake. These calculations were performed using a code from the CLAWPACK package (https://www.clawpack.org, (LeVeque et al., 2019)).

The characteristics of the model tsunami waves were calculated using the MGC software system (Chubarov et al., 2011; Shokin et al., 2008) based on an explicit two-step scheme of McCormack type for the classical shallow-water model (MacCormack*,* 1969). The model takes into account the nonlinearity of the wave process, the curvature of the earth's surface, the Coriolis force, and the bottom roughness.

We simulate the waves run-up on the coast in the local grid only. Nonlinear equations of the shallow water theory are solved numerically by the large particles method (Belotserkovsky and Davydov, 1982) which allows to obtain a well-balanced difference scheme. The method is based on an explicit difference scheme of the first order of approximation. Due to the irregularity of the coastal terrain, a fine grid must be used to obtain a numerical solution with sufficient resolution. Therefore, the use of a first-order accuracy scheme, which also has monotonous properties, is justifiable. Model validation, a description of the method, and its implementation (Rychkov et al., 2013) in the MGC software package were presented in the study of Shokin et al. (2015).

The following characteristics were calculated at each node of the local grid: the maximum amplitudes, wave heights, and flow velocities. Dynamics of the free surface and the flow velocity was recorded by the virtual gauges.

5. Probabilistic problem of tsunami zoning

As already mentioned above, the problem is to determine zones of the target area in which IMs of tsunami waves would not exceed the predetermined threshold values with a given recurrence rate. On the other hand, the threshold values that are not exceeded with a fixed (calculated by recurrence rate) probability for a given time interval can be determined using the results of the study.

Let us consider model earthquakes with epicenters located in the studied region and its surroundings, generating tsunami waves at a geographical point with coordinates (x, y). Let I be an IM of these waves. We consider "tsunami hazard by the threshold I_{thre}" of the events for which $I > I_{thre}$. The recurrence rate of such events W can be expressed as an integral:

$$W\left(I > I_{thre}, x, y\right) = \int_{\Omega} b\left(I\left(Q, x, y\right), I_{thre}\right) \cdot w\left(Q\right) dQ \qquad (3)$$

where Ω is the set in the space of parameters of the earthquakes, corresponding to all the tsunami sources; $Q \in \Omega$ is a collection of parameters of one source (in the context of the present work, the spatial coordinates of the centroid, the seismic source model parameters); $w(Q)$ is the recurrence rate (recurrence rate density) of the source with parameters Q (hereinafter, the variable Q will also be used to refer to the earthquake (event) parameters Q); $I(Q,x,y)$ is the IM value of the tsunami wave at the point (*x*,*y*) generated by the source *Q*;

$$b(a,b)=\begin{cases}1, & \text{if } a \geq b,\\ 0, & \text{else;}\end{cases} \quad \text{– binary indicator function.}$$

Integration in (3) is performed over a high-dimensional parametric space, and scenario calculation $I(Q,x,y)$ for each source requires significant computational resources. Therefore, the calculation of the integral (3) is conveniently carried out by the Monte Carlo method. To do this, function $w(Q)$ in (3) is written as

$$w(Q) = W_{all} \cdot p_{\Omega}(Q) \tag{4}$$

where W_{all} is the average recurrence rate of all earthquakes of the considered magnitude range in the studied area and $p_{\Omega}(Q)$ is represented as the probability density of the event Q. Then in (3) the recurrence rate $W(I > I_{thre}, x, y)$ can be considered as the mathematical expectation of the function $W_{all} \cdot b(I(Q,x,y), I_{thre})$ and evaluated as the average value of the sequence:

$$W(I > I_{thre}, x, y) \approx \frac{W_{all}}{N}\sum_{i=1}^{N} b(I(Q_i, x, y), I_{thre}) \tag{5}$$

where Q_i (parameters of the *i*-th earthquake) are independent realizations of a random variable Q that obeys the distribution $p_{\Omega}(Q)$, N is the length of the sequence Q_i.

6. Application of the Monte Carlo method

The method of calculating the integral (3) based directly on the relations (4) and (5), has serious disadvantages related to the peculiarities of the essential dependence of the functions $I(Q,x.y)$ and $w(Q)$ on the magnitude M_W. The fact is that both functions change in the considered magnitude range within a wide range and different directions. Fixing the other parameters in Q, the function $I(M_W, x, y)$ increases with increasing magnitude, and the value of $w(Q)$ at the same time decreases. As a result, the sequence of sources Q_i contains many events with small magnitudes, which correspond to small tsunami IMs $I(Q,x,y)$ and zero summands in sum (3). Determining the values $I(Q,x,y)$ for such events is unnecessary since, in the end, it does not affect the assessment of the recurrence rate of tsunami-hazardous events $W(I > I_{thre}, x, y)$.

This disadvantages are overcome by formal replacement of the magnitude dependence in $p_{\Omega}(Q)$ with another distribution that works better for calculations. We clearly distinguish the magnitude M_W writing $Q = (M_W, q)$, where q are the rest of parameters of the earthquake source. Then, using the formula for conditional probability, the relation (4) can be rewritten as:

$$w(Q) = W_{all} \cdot p_M(M_W) \cdot p_q(q \mid M_W) = W_{all}\frac{p_M(M_W)}{p_U(M_W)}[p_U(M_W) \cdot p_q(q \mid M_W)] = W_{all}\frac{p_M(M_W)}{p_U(M_W)}\tilde{p}_{\Omega}(\tilde{Q}) \tag{6}$$

where the distribution $p_U(M_W)$ can be chosen in any convenient way, the notation $\tilde{Q}$ indicates that the earthquake parameters now have a new density of distribution function $\tilde{p}_{\Omega}(\tilde{Q})$ on the set Ω, with the marginal density of the latter in magnitude is equal to $p_U(M_W)$. In this paper, the simplest variant with a uniform distribution in magnitude is used,

$$p_U(M_W) \equiv p_U = \frac{1}{\Delta M}. \tag{7}$$

Substituting $w(Q)$ from (6) into an integral (3), and, similarly, transforming it into a sum of type (5), we have

$$W\left(I > I_{thre}, x, y\right) \approx \frac{W_{all}}{\tilde{N}} \sum_{i=1}^{\tilde{N}} b\left(I\left(\tilde{Q}_i, x, y\right), I_{thre}\right) \cdot K\left(M_W^i\right), \tag{8}$$

where $K\left(M_W^i\right) = p_M\left(M_W^i\right) / p_U$. The expression (8) differs from (5) by the presence of weight factors $K(M_i)$ and the fact that the sequence of tsunami sources $\tilde{Q}_i$ (length $\tilde{N}$) is generated according to the new distribution (6) constructed in $\tilde{p}_\Omega(\tilde{Q}) = p_U \cdot p_q(q \mid M_W)$, which does not have sequence Q_i disadvantages. The synthetic catalog of earthquakes used in this study corresponds to the sequence $\tilde{Q}_i$.

The function $p_M\left(M_W\right)$ in (6) and (8) corresponds to the classical Gutenberg-Richter earthquake recurrence rate law. In this study, $p_M\left(M_W\right)$ was constructed from regional samples from catalogs of the International Seismological Center ISC (Storchak *et al.*, 2013; 2015; Di Giacomo *et al.*, 2018; ftp://ftp.isc.ac.uk/pub/isf/catalogue) with the addition of the results of studies of paleo-earthquakes of the Kamchatka Peninsula (Pinegina *et al.*, 2016, 2018). The density of distribution on magnitudes $p_M\left(M_W\right)$ was normalized so that the integral $\int_{\Delta M} p_M(M_W)dM$ was equal to 1 in the interval ΔM. Another normalizing parameter W_{all} (the average recurrence rate of all used earthquakes) included in (6) was calculated for $M_W \geq 7.8$ also using the data from the ISC catalog for the Kamchatka region: $W_{all} = 0.0777$ year^{-1}, which is approximately equivalent to seven earthquakes over 90 years.

7. Construction of probability maps of tsunami intensity thresholds

The results of probabilistic tsunami zoning are presented below in the form of maps of various tsunami IMs, which are achieved with a recurrence rate not exceeding the given value at each geographical point. The estimates are constructed independently at each point by repeatedly inverting the expression (8) relative to I_{thre} for a set of predetermined recurrence rate values $\hat{W}$.

In the first step, for each model earthquake $\tilde{Q}_i$ contained in the prepared catalog, scenario modeling of the tsunami wave transformation from the source to the coast of the study area is performed. As a result, a time-dependent characteristic of the tsunami wave $I_t(\tilde{Q}_i, x, y, t)$ is calculated at each point (x, y) of the area. The maximum of this function $I_{\max}(\tilde{Q}_i, x, y) = \max_t\{I_t(\tilde{Q}_i, x, y, t)\}$ is taken as an IM of the tsunami wave generated by the source $\tilde{Q}_i$ at the point (x, y). The resulting sequence $I_{\max}(\tilde{Q}_i, x, y)$ is sorted in descending order with the assignment of new ordinal indices *j*, so that $I_{\max}(\tilde{Q}_{j-1}) \geq I_{\max}(\tilde{Q}_j) \geq I_{\max}(\tilde{Q}_{j+1})$. The sort operation corresponds to a permutation of the terms in the sum (8).

Next, for each member of the resulting sequence, the recurrence rates of W_J are calculated using the formula $W_J\left(I > I_{thre_J}, x, y\right) = \frac{W_{all}}{\tilde{N}} \sum_{j=1}^{J} K(M_j)$, where I_{thre_J} successively takes values $I_{\max}(\tilde{Q}_i, x, y)$ with the addition of members in ascending order *J* until the sum is closest from below to the specified value $\hat{W}$. The value of the index $J_{\max}$ achieved, in this case, determines the position of the desired threshold IM $\hat{I}_{thre}\left(\hat{W}, x, y\right) = I_{\max}(\tilde{Q}_{J_{\max}}, x, y)$ corresponding to the specified recurrence rate $\hat{W}$, since approximate equality of the form (8) holds for it:

$$\hat{W} \approx \frac{W_{all}}{\tilde{N}} \sum_{j=1}^{\tilde{N}} b(I(\tilde{Q}_j, x, y), \hat{I}_{thre}) \cdot K(M_j),$$

in which for the first $J_{\max}$ members $b = 1$, and for the remaining ones $b = 0$. A similar construction is repeated for all points (x, y) of the study water area using the sequences $I_{\max}(\tilde{Q}_j, x, y)$ obtained at the previous stages of the study as the results of scenario calculations. The values $\hat{I}_{thre}\left(\hat{W}, x, y\right)$ form a map of the threshold values of the defined tsunami IM, which are reached with a recurrence rate not exceeding the specified value $\hat{W}$. Similar maps are constructed for different recurrence rate values $\hat{W}$.

The maps constructed in this way can also be interpreted in terms of the probability P of exceeding the threshold value of the tsunami IM in a given period of time T. Within the framework of the Poisson process model of seismic events, the corresponding probability is connected with the found above recurrence rate W by the relation

$$P = 1 - \exp(-WT). \quad (9)$$

The probabilities for different observation periods given in Table 1 correspond to the recurrence rates on average 1 time in 100, 500, and 1000 years (to shorten the writing, we will omit "on average"). For the most important in practice small values of the probability of exceeding the threshold $P <\sim 10\%$, the expression (9) takes the simple form: $P \approx WT$.

Table 1. Probability of exceeding the threshold values at certain observation periods with a fixed recurrence rate.

	T = 50	**T = 100**	**T = 500**	**T = 1000**
W = 1/100	39%	63%	99%	100%
W = 1/500	10%	18%	63%	86%
W = 1/1000	5%	10%	39%	63%

8. Tsunami zoning results

Based on the results of modeling the entire set of scenarios, the threshold values that can be reached at a given point in the local grid with a given recurrence rate were determined using the above technique.

The following series of figures demonstrates the dependence of the tsunami IMs in the cove on the presence or absence of protective structures (Fig. 5, Fig. 6) and on the specified recurrence rate (Fig. 7).

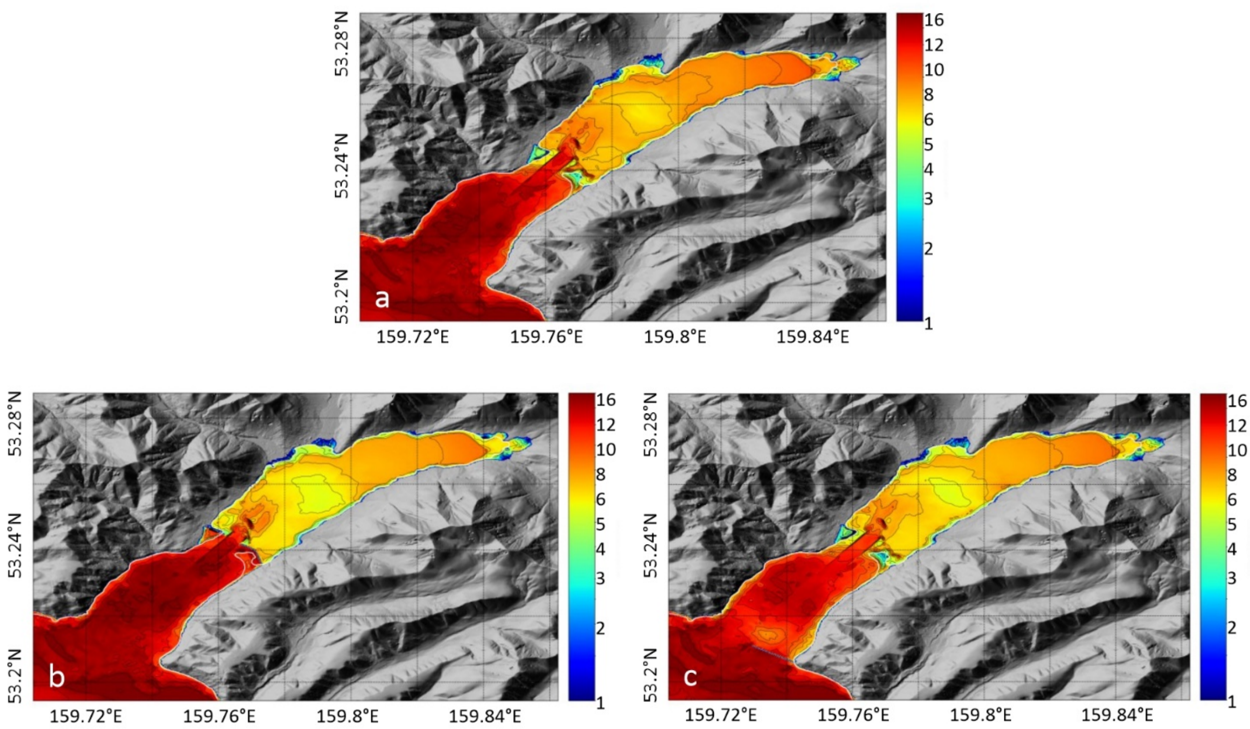

Fig. 5. Maximum threshold values for wave heights (m). Recurrence rate 1 time in 1000 years (5% probability of possible exceeding within 50 years): (*a*) – configuration with a channel without protective structures; (*b*) – configuration with a channel and protective structures in the narrow part of the cove; (*c*) – configuration with a channel and protective structure at the entrance to the cove

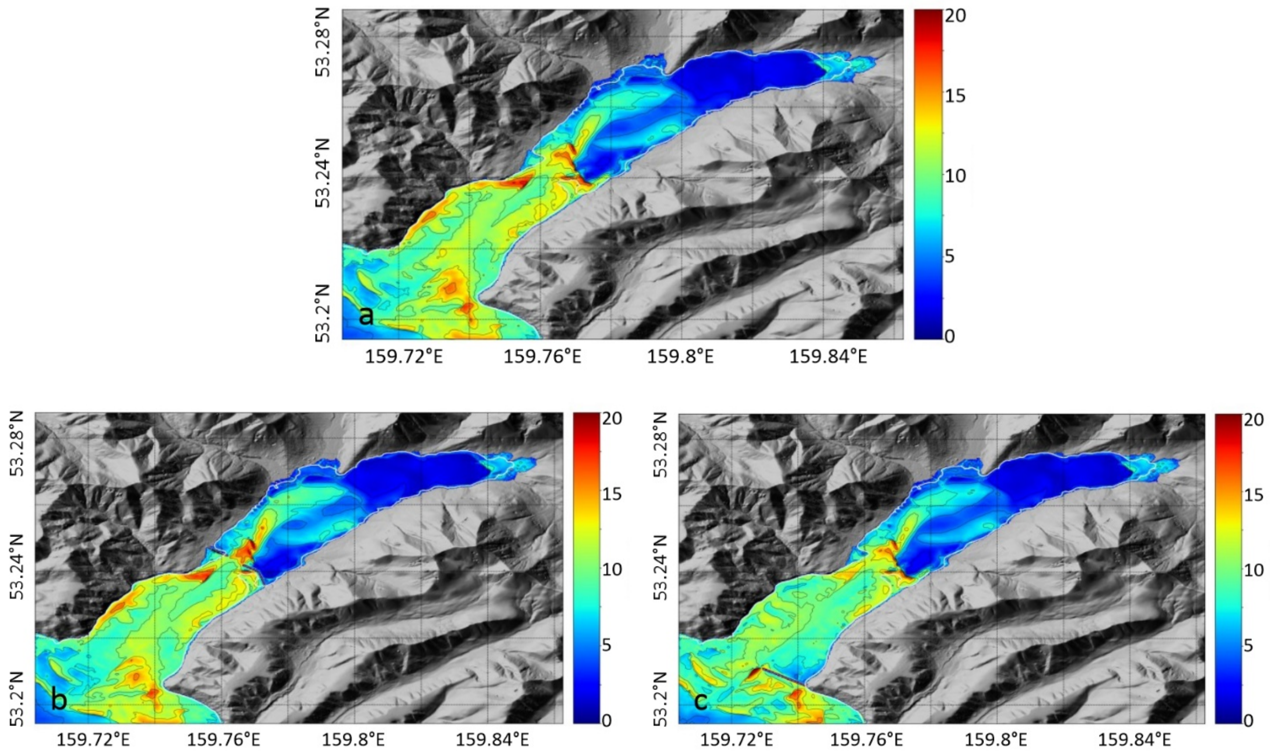

Fig. 6. Maximum threshold values for velocity modules (m/sec). Recurrence rate 1 time in 1000 years (5% probability of possible exceeding within 50 years): (*a*) – configuration with a channel without protective structures; (*b*) – configuration with a channel and protective structures in the narrow part of the cove; (*c*) – configuration with a channel and protective structure at the entrance to the cove

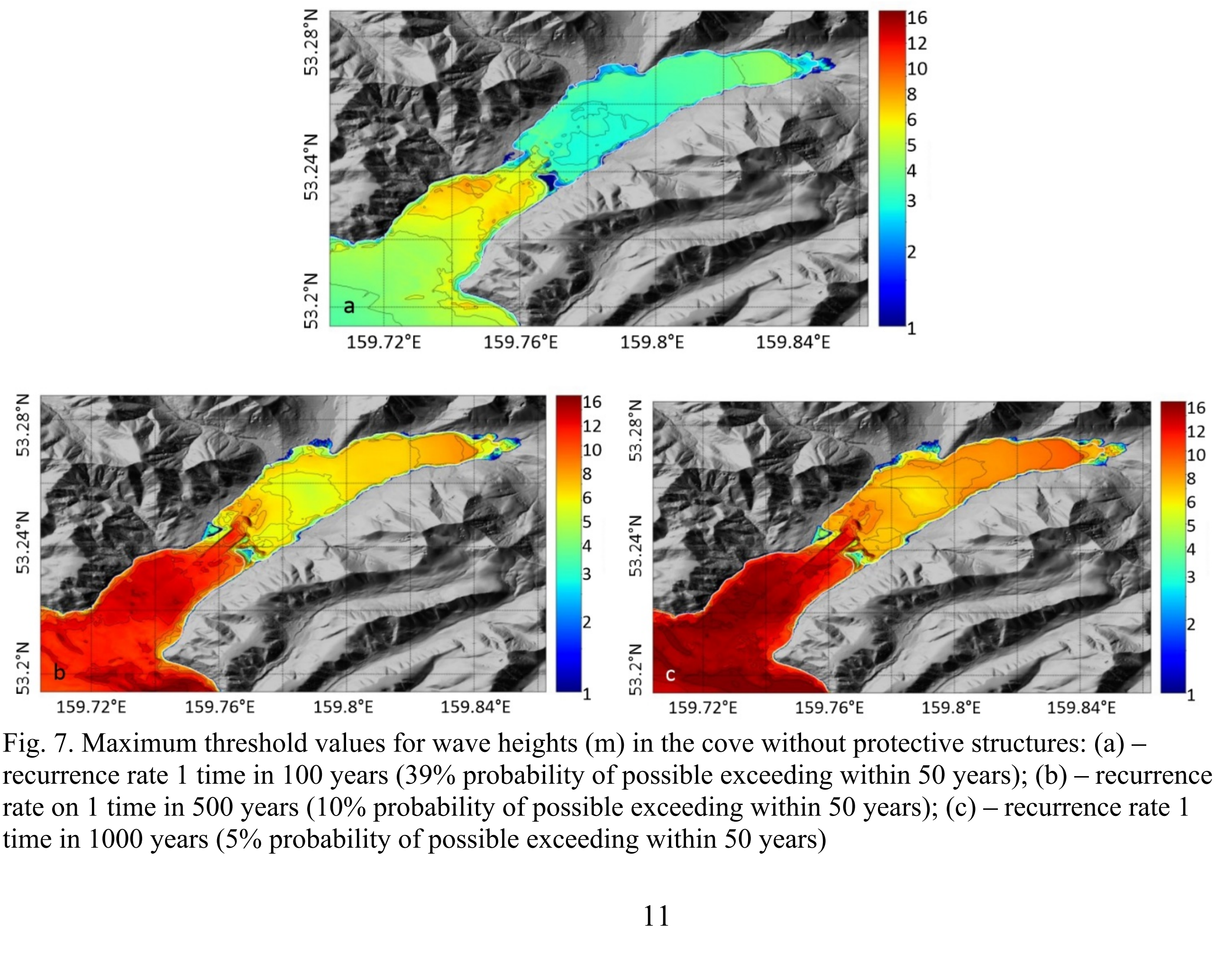

Fig. 7. Maximum threshold values for wave heights (m) in the cove without protective structures: (a) – recurrence rate 1 time in 100 years (39% probability of possible exceeding within 50 years); (b) – recurrence rate on 1 time in 500 years (10% probability of possible exceeding within 50 years); (c) – recurrence rate 1 time in 1000 years (5% probability of possible exceeding within 50 years)

The most significant result is the determination of the safest water zone areas. It provides the ability to select places suitable for the planned gas storage facilities. For the recurrence rate 1 time in 100 years, Fig. 8 shows sections for the following thresholds: wave height less than 3.5 m, amplitude less than 2 m, velocity less than 2 m/sec.

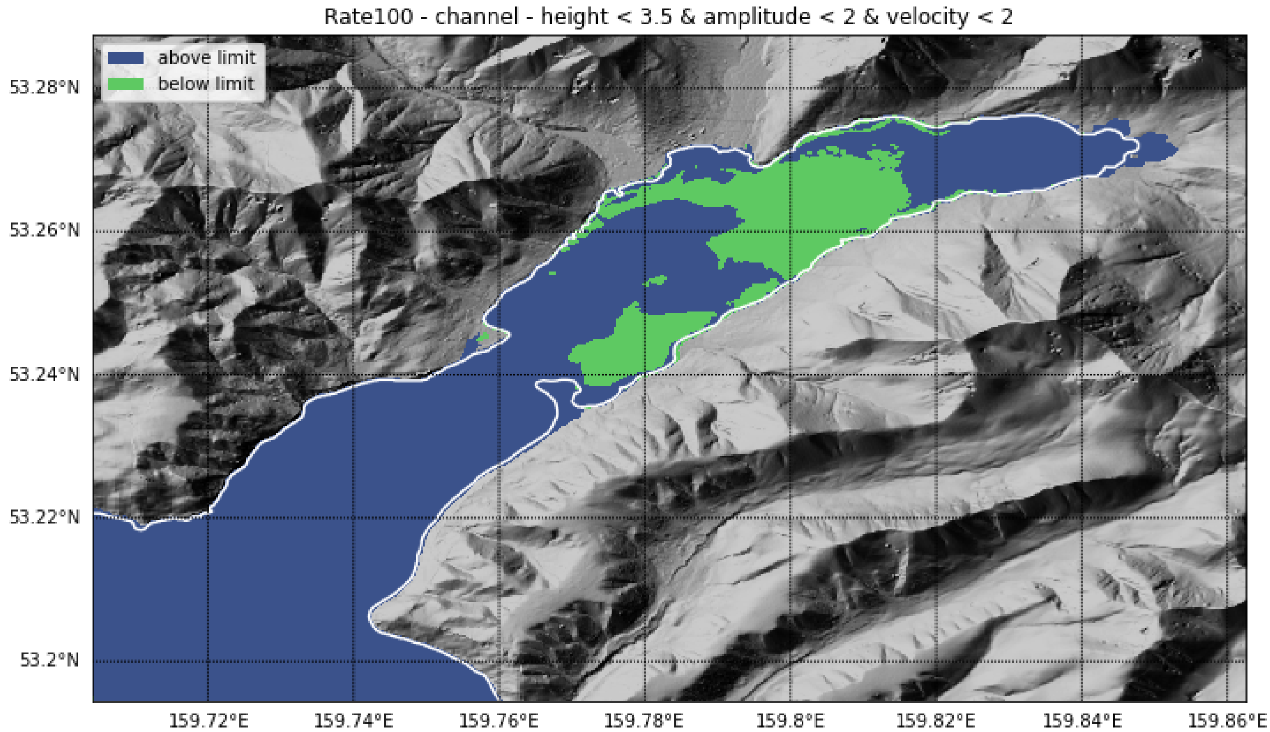

Fig. 8. Zoning of the water area in the absence of protective structures for the recurrence rate 1 time in 100 years at the threshold values for the wave height of 3.5 m, the amplitude of 2 m, the velocity modulus of 2 m/sec

Solving some engineering problems that are related, for example, to the assessment of the power impact of tsunami waves requires determining the wave dynamics at specified points in the water area. A "typical" scenario (Fig. 9) is selected to determine this kind of time histories for each recurrence rate considered. This scenario in some sense will be as close as possible to the received threshold values. The proximity was estimated using a quadratic L_2 measure of the difference between the maximum wave heights calculated for a typical scenario and the corresponding thresholds for the specified recurrence rate. The results obtained for the "typical" scenario constitute the necessary data sets, including the deviations of the free surface calculated at each step in time (see Fig. 10 for example) and the velocities along longitude and latitude. Note, however, that the results of "typical" scenarios are not exact matches for the corresponding thresholds calculated for the specified recurrence rate.

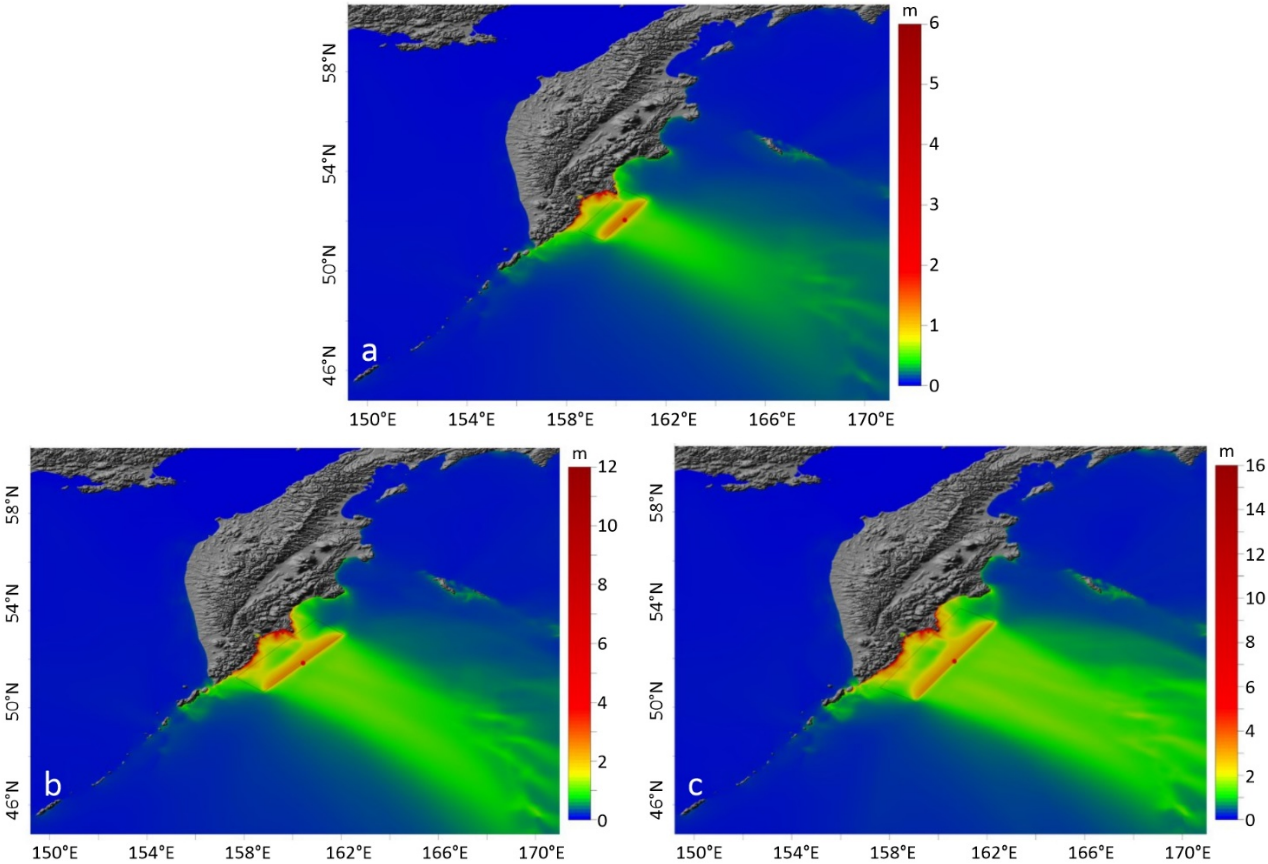

Fig. 9. The glows of amplitudes in the global grid with the image of rupture areas of "typical" sources for the recurrence rates: (*a*) – 1 time in 100 years; (*b*) – 1 time in 500 years; (*c*) – 1 time in 1000 years

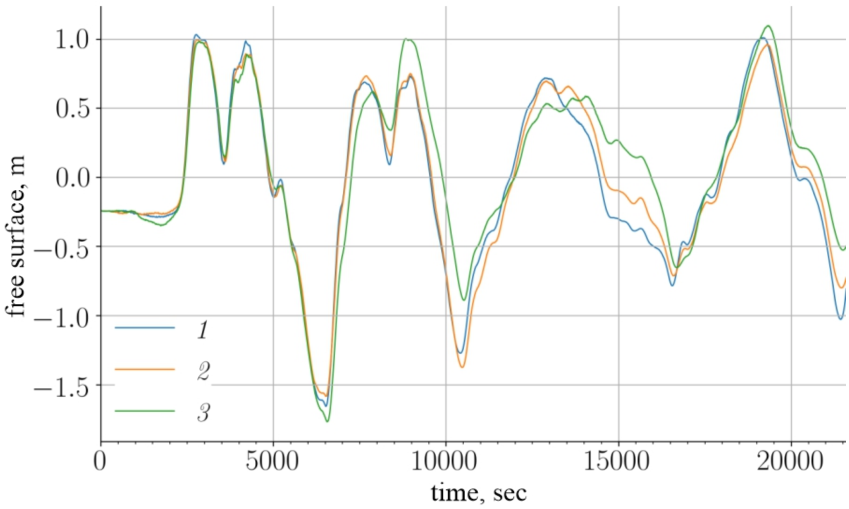

Fig. 10. The virtual gauge records, positioned in one of the proposed locations of hydraulic structures, for a "typical" source (close to the thresholds calculated for the recurrence rate 1 time in 100 years): 1 – for the water area configuration without protective structures; 2 – for the water area configuration with protective structures in the narrow part of the cove, 3 – for the water area configuration with protective structure at the entrance to the cove

In general, the results of the study demonstrate that the creation of the wave protection structure in the narrow part of the cove did not affect the wave heights for the recurrence rate 1 time in 100 years. For the recurrence rates 1 time in 500 and 1000 years, there is a decrease in these wave characteristics in the deep inner part of the cove, located behind the narrowing, but there is a significant increase of these characteristics in the area located in the vicinity of the structure itself and in the channel. At the same time, the creation of the wave protection structure at the entrance to the cove significantly reduces the wave height (up to 20%) in the outer part of the cove for all recurrence rates and practically does not affect the characteristics of wave regimes in the inner part of the water area.

The creation of wave protection structures in any of the considered configurations affects the flow velocities only in the vicinity of the structures and does not significantly affect it in the inner part of the cove. Creating the wave protection structures does not change the flooding area. In each variant of the water area configuration considered, a jet reflected from the shore is formed in the center of the inner part of the cove, and noticeable vortex structures are formed throughout the entire water area.

9. Conclusion

In this study, we propose the technique of near-field probabilistic tsunami zoning in order to determine the safest water areas of the Bechevinskaya Cove (the Kamchatka Peninsula), in which the values of the IMs of tsunami will not exceed the specified threshold values with the given recurrence rates. The method includes analysis of seismotectonics of the region, construction of the catalog of model tsunamigenic earthquakes, determination of their statistical characteristics, scenario numerical modeling of the dynamics of tsunami waves, calculations of the values of the IMs that can be exceeded with the given recurrence rates (on average 1 time in 100, 500, 1000 years). This method is implemented in the form of a set of algorithms that ensure the completeness of processing all input information and the implementation of all necessary mathematical models for computer simulation, pre- and post-processing.

Three configurations of the water area are considered, two of which include the protective structures in the different parts of the cove. The spatial distributions of the maximum wave heights and maximum velocities are provided for the considered recurrence rates. The calculations show that the protective structures do not considerably reduce the tsunami IMs in the inner part of the cove. Even in the absence of protective structures, we determine zones for the following thresholds values for the recurrence rate on average 1 time in 100 years: wave height less than 3.5 m, amplitude less than 2 m, velocity less than 2 m/sec.

Expanding the functionality of the methodology, in the authors' opinion, should be carried out in the direction of taking into account non-seismic mechanisms of generating tsunami waves – landslides, avalanches, meteorological, and volcanic. This will require not only attracting additional expertise, applying new mathematical models and computational algorithms, but also significantly expanding the set of input information. Serious attention should be paid to improving the efficiency of scenario calculations, both in terms of adapting computational algorithms to the architecture of modern high-performance computing devices, and in identifying the most significant parameters of phenomena that generate tsunami waves, to optimize the created sets of model events.

An important research area related to the development of measures for mitigating catastrophic manifestations of tsunami waves and reducing the damage they cause is the improvement of methodical, information, mathematical, and algorithmic framework to support the transition from tsunami hazard assessment (PTHA) to tsunami risk assessment (PTRA).

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References

Beisel, S.A., Gusyakov,V.K., Rychkov, A.D., Chubarov, L.B., Shokin, Yu.I., 2014. Algorithms and Methodologies of Numerical Modeling of Tsunami Waves Runup to Assess the Characteristics of the Waves Runup on the Russian Far-East Coast. In: Proceedings of XII All-Russian Conference "Advanced Technologies of Hydroacoustics and Hydrophysic", Saint-Petersburg, Russia, pp. 228-230 (in Russian).

Belotserkovsky, O.M., Davydov, Yu.M. Large Particle Method in Gasdynamics. Nauka, Moscow, 392 p., 1982. (In Russian).

Castaños, H., Lomnitz, C., 2002. PSHA: Is it science? Eng. Geol. 66, 315–317. https://doi.org/10.1016/S0013-7952(02)00039-X

Chubarov, L. B., Babailov, V. V., Beisel, S. A. “Program for calculating parameters of seismogenetic tsunami waves MGC,” State Registration Certificate of Computer Program No. 2011614598.

Di Giacomo, D., Engdahl, E.R., Storchak, D.A., 2018. The ISC-GEM Earthquake Catalogue (1904–2014): status after the Extension Project. Earth Syst. Sci. Data 10, 1877-1899. https://doi.org/10.5194/essd-10-1877-2018

Grezio, A., Babeyko, A., Baptista, M. A., Behrens, J., Costa, A., Davies, G., Thio, H. K., 2017. Probabilistic Tsunami Hazard Analysis: Multiple sources and global applications. Reviews of Geophysics 55, 1158–1198. https://doi.org/10.1002/2017RG000579

Gusiakov, V. K., 1978. Residual displacements on the surface of elastic half-space. In: Conditionally Correct Problems of Mathematical Physics in Interpretation of Geophysical Observations. Vychisl. Tsentr Sib. Otdel. RAN, Novosibirsk, pp. 23–51 (in Russian).

Gusiakov. V.K., 2016. Tsunamis on the Russian Pacific Coast: History and Current Situation. Russian Geology and Geophysics 57 (9), 1259–1268. https://doi.org/10.1016/j.rgg.2016.08.011

Gusiakov, V. K., 2017. Methods and problems of tsunami hazard assessment of marine coasts. Fundamentalnaya i Prikladnaya Gidrofizika 10 (3), 26–38 (In Russian). https://doi.org/10.7868/S2073667317030029

Gusev, O.I., Chubarov, L.B., 2018. On the use of telescopic nested grids in computations of tsunami propagation. In: Proceedings of XIV All-Russian conference “Advanced technologies of hydroacoustics and hydrophysics”, Saint-Petersburg, Russia, pp. 224–226 (In Russian).

Gusiakov, V.K., Kikhtenko, V.A., Chubarov, L.B., Shokin, Yu.I., 2019. Regional tsunami hazard maps for the Far East coast of Russian Federation built in the framework of the PTHA methodology. Computational Technologies 24 (1), 55–72 (In Russian). https://doi.org/10.25743/ICT.2019.24.1.005

Hall, J., 2006. GEBCO centennial special issue – Charting the secret world of the ocean floor: The GEBCO project 1903–2003. Mar. Geophys. Res. 27, 1–5. https://doi.org/10.1007/s11001-006-8181-4

Kulikov, E.A., Ivashchenko, A.I., Medvedev, I.P., Yakovenko, O.I., Kovachev, S.A., 2016. On tsunami hazard in the Arctic Region. Arctic: ecology and economy 3 (23), 38–49 (In Russian).

LeVeque, R. J., Berger, M. J., et al. Clawpack software. www.clawpack.org (http://www.clawpack.org) (accessed 15 August 2019).

Lorito, S., Selva, J., Basili, R., Romano, F., Tiberti, M.M., Piatanesi, A. 2015. Probabilistic hazard for seismically induced tsunamis: accuracy and feasibility of inundation maps. Geophys. J. Int. 200, 574–588. https://doi.org/10.1093/gji/ggu408

Løvholt, F., Fraser, S., Salgado-Gálvez, M., Lorito, S., Selva, J., Romano, F., Suppasri, A., Mas, E., Polet, J., Behrens, J., Canals, M., Papadopoulus, G.A., Schäfer, A., Zamora, N., Chacón-Barrantes, S., Wood, N., Aguirre-Ayerbe, I., Zorrilla, I., Rodríguez, M., Baptista, M., 2019. Global Trends in Advancing Tsunami Science for Improved Hazard and Risk Understanding. Contributing Paper to GAR, 50 p.

MacCormack, R.W., 1969. The Effect of viscosity in hypervelocity impact cratering. AIAA Paper 69–354. https://doi.org/10.2514/2.6901

Mitchell, Don P., 1991. Spectrally optimal sampling for distribution ray tracing. SIGGRAPH Comput. Graph. 25 (4), 157–164. https://doi.org/10.1145/127719.122736

Morin, P., Porter, C., Cloutier, M., Howat, I.M., Noh, M.J., Willis, M., Bates, B., Willamson, C., Peterman, K., 2016. ArcticDEM, a publically available, high resolution elevation model of the Arctic. EGU Gen. Assem. Conf. Abstr. 18, p.8396.

Mulargia, F., Stark, P.B., Geller, R.J., 2017. Why is Probabilistic Seismic Hazard Analysis (PSHA) still used? Phys. Earth Planet. Inter. 264, 63–75. http://dx.doi.org/10.1016/j.pepi.2016.12.002

Okada, Y., 1985. Surface deformation due to shear and tensile faults in a half-space. Bull. of the Seismolog. Soc. of America. 75 (4), 1135–1154.

Papazachos, B.C., Scordilis, E.M., Panagiotopoulos, D.G., Papazachos C.B., Karakaisis, G.F., 2004. Global Relations Between Seismic Fault Parameters and Moment Magnitude of Earthquakes. Bulletin of the Geological Society of Greece XXXVI, 1482-1489. https://doi.org/10.12681/bgsg.16538

Park, H., Cox, D.T., 2016. Probabilistic assessment of near-field tsunami hazards: inundation depth, velocity, momentum flux, arrival time, and duration applied to Seaside. Oregon. Coast Eng. 117, 79–96. https://doi.org/10.1016/j.coastaleng.2016.07.011

Park, H., Cox, D.T., Barbosa A.R., 2018. Probabilistic Tsunami Hazard Assessment (PTHA) for resilience assessment of a coastal community. Nat. Hazards. 94 (3), 1117-1139. https://doi.org/10.1007/s11069-018-3460-3

Pinegina, T.K., Bazanova, L.I., 2016. New data on characteristic of historical tsunami on the coast of Avacha Bay (Kamchatka). Bulletin of Kamchatka regional association "Educational-scientific center": Earth sciences 31 (3), 5– 17 (In Russian). DOI: 10.31431/1816-5524-2016-3-31-%p

Pinegina, T.K., Bazanova, L.I., Zelenin, E.A., Bourgeois, J., Kozhurin, A.I., Medvedev, I.P., Vydrin, D.S., 2018. Holocene tsunamis in Avachinsky Bay, Kamchatka, Russia. Pure and Applied Geophysics 175 (4), 1485-1506. https://doi.org/10.1007/s00024-018-1830-0

Rychkov, A. D., Beisel, S. A., Chubarov, L. B. Computer Program: “Module for calculation of runup of tsunami waves on a coast RunUp-LP”. State Registration Certificate of Computer Program No. 2013617980.

Shokin, Yu.I., Babailov, V.V., Beisel, S.A., Chubarov, L.B., Eletsky, S.V., Fedotova, Z.I., Gusyakov, V.K., 2008. Mathematical modeling in application to regional tsunami warning systems operations. In: E.Krause et al. (Eds.): Comp. Science & High Perf. Computing III, Notes on Numerical Fluid Mechanics and Multidisciplinary Design (101), pp. 52–68. https://doi.org/10.1007/978-3-540-69010-8_6

Shokin, Y.I., Beisel, S.A., Rychkov, A.D., Chubarov L. B., 2015. Numerical simulation of the tsunami run-up on the coast using the method of large particles. Math. Models Comput. Simul. 7, 339–348. https://doi.org/10.1134/S2070048215040109

Storchak, D.A., Di Giacomo, D., Bondár, I., Engdahl, E.R., Harris, J., Lee, W.H.K., Villaseñor, A., Bormann, P., 2013. Public Release of the ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009). Seism. Res. Lett. 84 (5), 810-815. https://doi.org/10.1785/0220130034.

Storchak, D.A., Di Giacomo, D., Engdahl, E.R., Harris, J., Bondár, I., Lee, W.H.K., Bormann, P., Villaseñor, A., 2015. The ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009): Introduction. Phys. Earth Planet. Int. 239, 48-63. https://doi.org/10.1016/j.pepi.2014.06.009.