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OCEANOLOGY

A Methodology for Mapping Tsunami Hazards and Its Implementation for the Far Eastern Coast of the Russian Federation

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Abstract—Overview maps of tsunami hazards for the Far Eastern coast of the Russian Federation are created. The methodological principles of the PTHA (Probabilistic Tsunami Hazard Assessment) approach are discussed, as are the problems of constructing seismotectonic models of the main tsunamigenic zones, mathematical models and algorithms for calculating probability estimates of tsunami hazards, and some problems of applying the PTHA methods related both to the lack of observation data and the complexity in performing a large volume of numerical scenario simulations. Examples of overview maps of tsunami hazards for various recurrence intervals, constructed using the PTHA methodology and presented using the "WTMap" application, are given.

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A probabilistic tsunami hazard assessment is performed using the PTHA (Probabilistic Tsunami Hazard Assessment) methodology [1–3], implemented in the construction of seismotectonic models of tsunamigenic zones that pose a threat to the coast, and numerical simulation of the occurrence of a tsunami near coastal sites. Only the most significant seismogenic tsunamis are taken into account (amounting to about 95% for the Far Eastern region of the Russian Federation [4]).

The methodology is based on the hypothesis suggesting that the coastal impact of a tsunami with a given intensity is represented as a Poisson flux of events, which is characterized by the relation

$$P(I(s) > I_{\text{thre}}, T) = 1 - \exp(W(I(s) > I_{\text{thre}})T), \quad (1)$$

where P is the probability of an event; T is the time period; $I(s)$ is the characteristic of a tsunami hazard in a protected coastal area, I_{thre} is the threshold value of this characteristic; s is the wave height at the water boundary, and $W(I(s) > I_{\text{thre}})$ is the average exceedance frequency (recurrence) of the value I_{thre}, which determines completely the flux of events. Owing to additivity of the Poisson fluxes, the value $W(I(s) > I_{\text{thre}})$ is represented as the sum of frequencies of all likely events with $I(s) > I_{\text{thre}}$:

$$W(I(s) > I_{\text{thre}}) = \int_{\Omega} b(I(s|Q), I_{\text{thre}})w(Q)dQ, \quad (2)$$

where Ω is a continuous space of tsunamigenic earthquake source parameters; $Q \in \Omega$ is the element of this space; $I(s|Q)$ is the wave height in a defended site due to the impact of the source Q; $b(x,y)$ is the indicator function, equal to 1, if $x > y$, and 0, otherwise; $w(Q)$ is the average recurrence interval of an event with the source Q, in a sense implying the density of the event fluxes. The space Ω and recurrence intervals $w(Q)$ are determined from the seismotectonic model of the region with a certain determination error, which is explained by the lack of statistics on the observed events, specifically in a high magnitude area. The value $I(s|Q)$ is sought by numerical simulation of the wave propagation.

The choice of the integration algorithm in [2] is caused by the multidimensionality of the space Ω, the aim to decrease the number of the integration knots while retaining the required accuracy, and the lack of a need to recalculate the values when the seismotectonic model is modified.

The totality of the parameter Q sets, densely covering the space Ω, is created using expert estimates. The study area is divided into conditionally homogeneous zones (CHZ), inside which the seismicity characteristics are constant. A likely magnitude range is given for each CHZ, which is divided into subranges, and the space Ω is divided into classes of Ω_i. The recurrence

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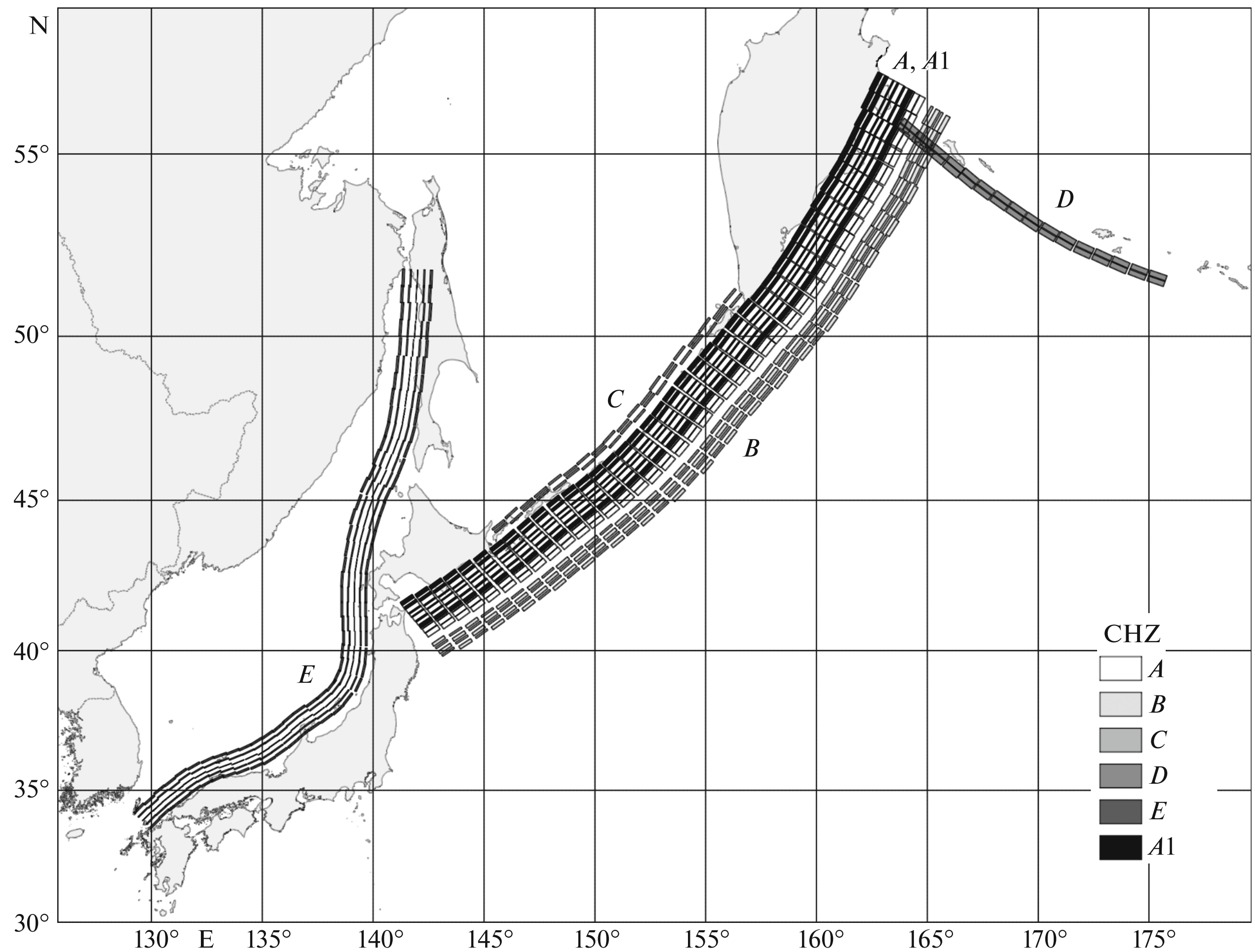

Fig. 1. The fault plane projections in the sources of model earthquakes with magnitude $M_w = 7.2$ in conditionally homogeneous zones.

interval of each class $w(\Omega_i)$ is estimated either by the number of relevant events in the catalog, or by extrapolation of the Gutenberg–Richter law to a high magnitude domain.

Based on expert estimates, a set of representative sources $\{Q_i\}$ is constructed for the i-th class, and the recurrence intervals of the sources are divided by all representatives. Then

$$W(I(s) > I_{\text{thre}}) = \sum_i \frac{N_i(I(s) > I_{\text{thre}})w(\Omega_i)}{M_i},$$

where M_i is the number of model sources of the i-th class; $N_i(I(s) > I_{\text{thre}})$ is the number of sources providing exceedance of the threshold values.

The values of $I(s|Q)$ are determined by modeling tsunami propagation using the software complex MGC [5], implementing the finite-difference algorithm based on the MacCormack scheme [6]. This algorithm approximates nonlinear shallow water equations accounting for the Earth's sphericity and the Coriolis force.

The piston tsunami model is used, which suggests that static residual bottom displacements occur due to the impact of the internal spatial dislocation source [7], thus determining the initial perturbation of the ocean surface at the source.

To construct the overview tsunami hazard maps for the Far Eastern coast of Russia based on modern concepts on the seismotectonics of the region, a totality of 2552 model sources has been created (Fig. 1), which was comprised in six CHZs. In the Kuril–Kamchatka region, zone A, approximated by a source system (M_w ranging from 7.2 to 9.0) with movements oriented across the strike of the island arc, and zone A1, implementing a different type of mechanisms [8] with reverse-fault movements along the oceanward steeply-dipping fault planes, have been formed.

A steeply-dipping normal fault mechanism of movements along the planes subparallel to the deep-sea trench strike is typical of zone B. Here a system of four chains of sources (M_w ranging from 7.2 to 8.4) is constructed. The model is also complemented by a

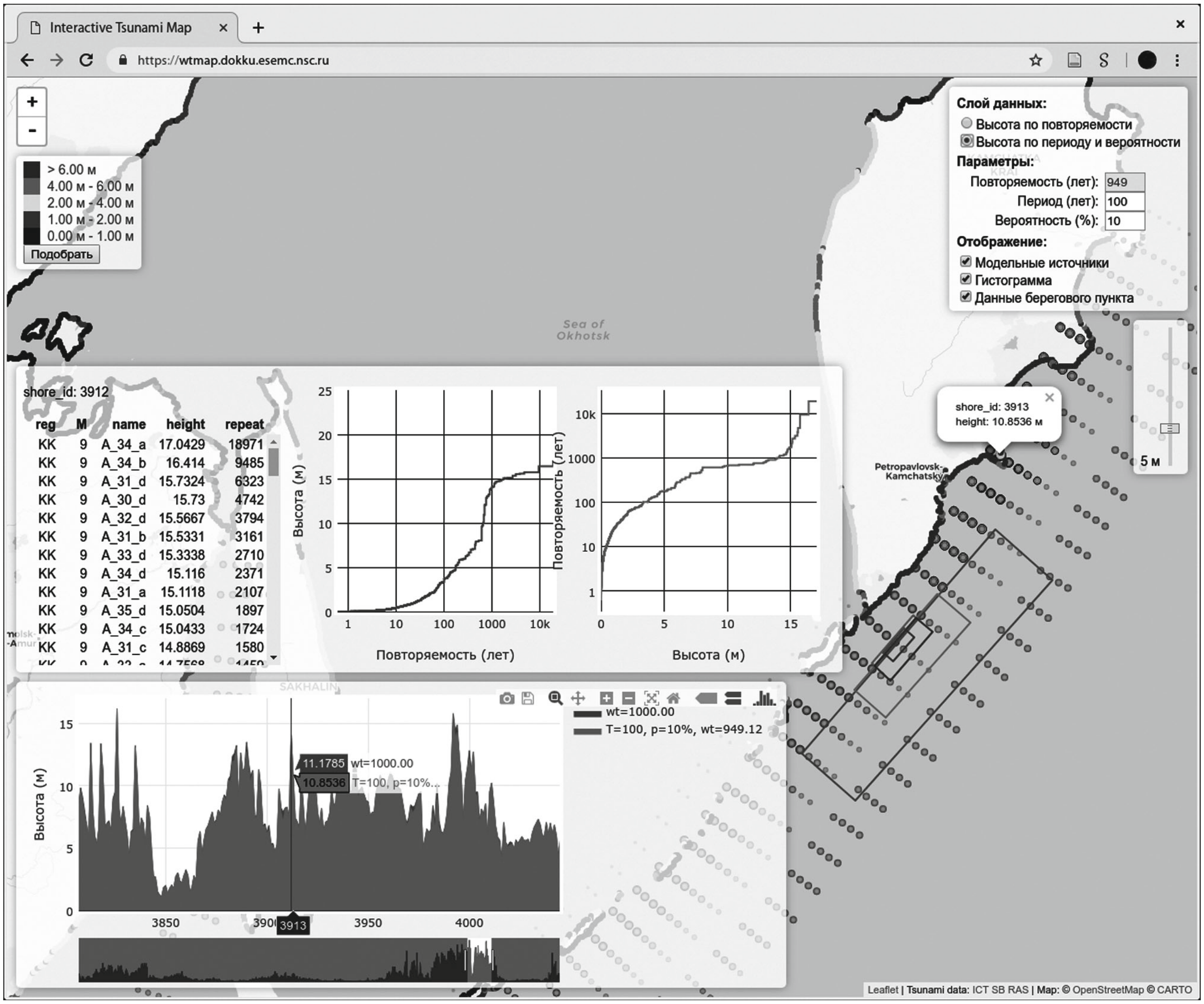

Fig. 2. WTMap web-application.

double chain of sources (M_w = 7.2) displaying the reverse-fault mechanism of movements along differently oriented fault planes dipping beneath the ocean and the Sea of Okhotsk (zone C).

In the western part of the Aleutian island arc, zone D was approximated by a double chain of sources with a complete set of magnitudes M_w = 7.2–9.0 and the mechanisms of oblique underthrust along the main lithospheric interface gently dipping beneath the Bering Sea. In the Sea of Japan, the CHZ labelled E was approximated by a system of five chains of sources with magnitudes M_w = 7.2, 7.8, and 8.4, with reverse fault movements along the subvertical fault planes.

To estimate the recurrence intervals, the model events were grouped into 13 classes according to magnitude and reference to the CHZ. The recurrence intervals of events in a given magnitude range within the CHZ (or their clusters) were divided by the representativity period of the relevant class in the catalog [9]. A total of 70% of the historical events in the overlapping zones A and A1 are referred to zone A. In zone E, the recurrence interval was determined by linear approximation of the Gutenberg–Richter law with extrapolation to a high-magnitude domain.

The Web application WTMap [10] allows for the construction and presentation of the maps showing the along-coastal wave height distribution with a given average exceedance recurrence interval for the threshold wave height value or for the given observation periods and the exceedance probability with recalculation according to formula (1). The model earthquake epicenters are plotted on the map of the region (Fig. 2). The color of the coastal line corresponds to the wave height estimates with a given average exceedance recurrence interval. When moving the cursor to a certain coastal point on the map, sources are lighted, showing the nucleated wave heights at this point

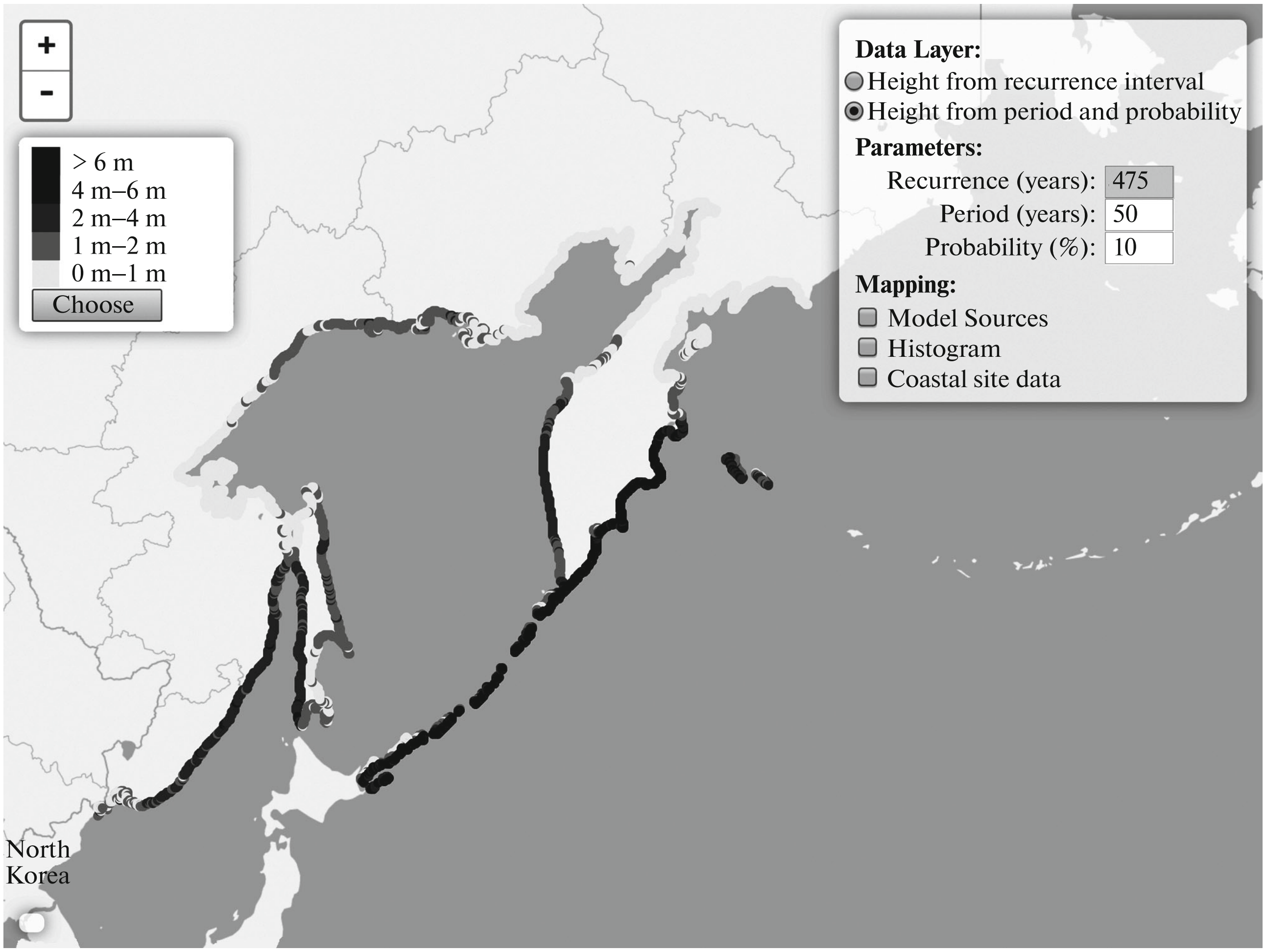

Fig. 3. An example of the calculated tsunami hazard map for the Far Eastern coast of the Russian Federation obtained in the framework of the PTHA methodology: $P = 10\%$, $T = 50$ years, recurrence interval of one time in 475 years.

exceeding a given wave height value, and the table lists the calculated wave heights of all model sources for the point. The expected wave height versus the recurrence interval dependences and the distribution of the wave height values for a chosen coastal point and its vicinity and along the entire Far Eastern coast are also shown. When choosing the epicenter, the site projections with fault planes of the sources producing different magnitudes are shown. The WTMap assumes interactive parameter variation of the information presented.

The analysis of the constructed maps (see, for example, Fig. 3) shows that the tsunamis nucleated due to earthquakes that occurred on the continental slope of the Kuril–Kamchatka subduction zone were mostly hazardous (wave heights reached up to 5–6 m). On the western coast of the island arc, the same earthquakes result in lower wave heights (1–2 m). The waves are expected to be less than 1 m high on the remainder of the coastal area of the Sea of Okhotsk except for part of the eastern coast of Sakhalin and the western coast of Kamchatka. The tsunamigenic earthquake sources located in the eastern part of the Sea of Japan, which are capable of generating waves of up to 3–4 m height, mostly affect the coastal area of Primorskii krai.

The main problem of the PTHA methodology is related to the construction of the models for tsunamigenic zones, which are frequently developed based on incomplete and nonreliable information on the geological structure and seismotectonic regime of these zones.

Another problem concerns searching for ways of increasing the computational labor expenditure for scenario calculations needed to obtain tsunami hazard estimates for long-term recurrence intervals. This is possible due to the utilization of newly developed mathematical models and algorithms and modern hardware and software. The development of digital elevation models of the bottom relief and land surface with the necessary accuracy of the obtained results entails certain difficulties.

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REFERENCES

1. W. Power and G. Downes, in *Volcanic and Tectonic Hazard Assessment for Nuclear Facilities,* Ed. by C. Connor, N. Chapman, and L. Connor (Univ. Press, Cambridge, 2009), pp. 276–306. https://doi.org/10.1017/CBO9780511635380.012
2. J. Knighton and L. Bastidas, Nat. Hazards **78**, 699–723 (2015). https://doi.org/10.1007/s11069-015-1741-7
3. A. Grezio, A. Babeyko, M. A. Baptista, et al., Rev. Geophys. **55**, 1158–1198 (2017). https://doi.org/10.1002/2017RG000579
4. V. K. Gusiakov, Russ. Geol. Geophys., **57** (9), 1259–1268 (2016). https://doi.org/10.15372/GiG20160901
5. Yu. I. Shokin, V. V. Babailov, S. A. Beisel, et al., in *Comput. Sci. and High Perform. Computing III: Notes on Numerical Fluid Mechanics and Multidisciplinary Design,* Ed. by E. Krause, Yu. I. Shokin, M. Resch, and N. Shokina (Springer-Verlag, Berlin, 2008), Vol. 101, pp 52–68. https://doi.org/10.1007/978-3-540-69010-8_6
6. R. W. MacCormack, J. Spacecraft Rockets **40** (5), 757–763 (2003). https://doi.org/10.2514/2.6901
7. Y. Okada, Bull. Seismol. Soc. Am. **82** (2), 1018–1040 (1992). https://doi.org/10.1016/0148-9062(86)90674-1
8. L. I. Lobkovskii and O. G. Sorokhtin, in *Oceanology: Ocean Geophysics* (Nauka, Moscow, 1979), pp. 194–203.
9. *HTDB/WLD (Historical Tsunami Database for the World Ocean), 2000 BC to Present* (Tsunami Lab., ICMMG SB RAS, Novosibirsk, 2018). http://tsun.sscc.ru/nh/tsunami.php.
10. V. A. Kikhtenko, V. K. Gusyakov, and L. B. Chubarov, PC Software Certificate no. 2017618398 (2017). https://wtmap.dokku.lesemc.nsc.ru.

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