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The problem of estimating the accuracy of the tsunami activity parameters*

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Abstract. The subject of the article is the theoretical development of the probabilistic model for a Poisson-type tsunami sequence that is consistent with data on the manifestations of historical events, in order to obtain estimates of the accuracy of the tsunami activity parameters. An example of a tsunami recurrence function, which is the most important quantitative characteristic of tsunami activity for the Port of Malokurilskoye, one of the places in the South Kuril Islands region with the most reliable tsunami height dataset, was created on the basis of a theoretical essay. An explanation for the weak statistical stability of all large values of the tsunami heights, especially for the largest one in the series of observations, was given based on the probability density functions of the ranked tsunami heights. In particular, it means, for example, that the maximum tsunami height recorded at a certain location during a 30-year observation period should be correlated with a wide range of possible recurrence periods of about 10 to 100 years. Synthetic catalogs of the tsunami heights, built for the Port of Malokurilskoye, showed that the tsunami height datasets with a duration of at least 250 or 500 years without gaps are needed to obtain the tsunami activity parameters with an acceptable accuracy of 10 or 5 %.
The most important results are the analytical equations for the variances of estimates of the tsunami activity parameters, which characterize the accuracy of these estimates, depending on a priori unknown values of the tsunami activity parameters and the amount of data used.

Keywords: tsunami, run-up height, recurrence, tsunami activity, tsunami hazard, probabilistic model, statistics

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Introduction

Tsunami is a dangerous natural phenomenon that is a wave process in the ocean, usually caused by a strong underwater earthquake, less often by an eruption of a volcano located in the water, or by a giant landslide [1]. A large part of the Russian Far East coast is affected by the tsunami to varying degree. The most catastrophic tsunami in November, 1952, caused the death of several thousand people and practically destroyed all settlements on the coast of the Northern Kuril Islands and the south of Kamchatka (Fig. 1) [2].

The relatively recent tsunami of November 15, 2006, was accompanied by run-ups up to 20 m high in the Central Kuril Islands. The tsunami did not cause serious negative aftermath just due to the lack of a permanent population and infrastructure on the islands [3]. The tsunami of March 11, 2011, which caused catastrophic aftermath on the coast of Japan, came to the South

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Kuril Islands being sufficiently weakened and, nevertheless, caused a serious negative impact on the island port industry, since it was accompanied by heavy coastal ice movement [4].

The presence of settlements, ports and industry in the coastal zone of the Russian Far East, as well as plans for the further development of this region, make the task of estimating the tsunami hazard extremely urgent. And, most importantly, such estimates should be quantitative and accompanied by objective assessments of their accuracy and/or possible uncertainty: underestimation of the risk may lead to unnecessary damage and casualties, while the overestimation would entail unnecessarily expensive engineering protection and/or inadequate prevention and evacuation measures.

After the catastrophic tsunamis in the Indian Ocean in 2004 and off the northeast coast of Honshu (Japan) in 2011, the development and use of various versions of the Probabilistic Tsunami Hazard Assessment (PTHA) technology for different coasts became generally accepted. It is within the framework of the probabilistic approach that most modern tsunami zoning maps have been created [5–10]. The lack of reliable information about the manifestations of historical tsunamis is compensated by seismic data in PTHA technology. Indeed, it is strong earthquakes in the ocean that cause most of the known tsunamis. However, a model equipped with additional seismic information becomes multi-parametric and complex. In addition, the use of seismic data automatically involves some problematic seismological regularities, such as the use of the Gutenberg–Richter law for the strongest earthquakes [11]. These are some of the reasons that make obtaining reliable estimates of the accuracy of the tsunami hazard parameters rather problematic.

It should be noted that recent reviews [12–14] have confirmed the existence of serious problems in estimating the accuracy and possible uncertainties regarding the quantitative estimates of tsunami hazard derived from such probability models.

This article develops a probabilistic model of tsunami manifestations, which is based on the use of reliable data on run-up heights of the historical tsunamis at a certain place – the Port of Malokurilskoye (Southern Kuril Islands) (Fig. 2). The model allows us to evaluate the physical parameters that determine the nature of tsunami activity and, accordingly, tsunami hazard. This approach also allows the progress to be made in the theoretical description of the tsunami recurrence function and, most importantly, to obtain analytical formulas for variances of the tsunami activity parameters, characterizing their accuracy, depending on the amount of data used.

Fig. 1. View of the central part of the Severo-Kurilsk city, destroyed by the 1952 tsunami. *Photo by L. Bondarenko*

Tsunami height recurrence functon

The nature of tsunami manifestations on the coast is determined by many factors, and these are the features of tsunami generation by various sources located in space and time, as well as regular and irregular features of bathymetry along the wave propagation path and in the coastal zone. Therefore, the data on tsunami heights recorded at a certain point on the coast during a time period T should be considered as a random series and ranked for each point in accordance with the value

$$h_1 \geq h_2 \geq h_3 \geq \ldots \qquad (1)$$

The tsunami recurrence function (TRF) is the most important quantitative characteristic of tsunami activity. According to the definition, the TRF is the average frequency of events at a given location with a height equal to or greater than the threshold value h:

$$\varphi(h) = \frac{\overline{N(\text{tsunami height} \geq h)}}{T}, \qquad (2)$$

where N is the number of such events that occurred during the time period T.

This theoretical essay mainly contains a summary of the theory related to the TRF [15–17]. The tsunami process is explicitly or implicitly assumed to be homogeneous over time, since only the data on the manifestations of the historical tsunami over the past few centuries with gaps are available, as well as extremely interesting and very promising, but the rather problematic, data about the palaeotsunamis [18, 19] related mainly to the mid- to late-Holocene. In other words, we can operate incomplete datasets for a very short time period on a geological scale.

It is shown, that for the tsunami heights $h > 0.5$ m the TRF in (2) can be approximated by the exponent [16]:

$$\varphi(h) = f \cdot e^{-\frac{h}{H^*}}. \qquad (3)$$

The parameters, which appear in this formula, have a transparent physical meaning: f is an asymptotic frequency of strong tsunami in the region, which slowly changes along the coast and can be considered regional constant, and parameter H^* is a characteristic tsunami height, and this parameter is also local and changes significantly along the coast. Together, these parameters characterize tsunami activity in the study point of the coast, and the knowledge of them allows describing the dynamics of the tsunami manifestations. The main problem can now be formulated as follows: the f and H^* parameters of tsunami activity and their variances for a given point of the coast need to be estimated on the basis of a series of historical data (1) on tsunami heights.

The dependence (3) is a linear on a semilogarithmic scale by the tsunami height h $\ln\varphi(h) = \ln f - \frac{1}{H^*}h$. In order to plot such linear regressive model by the least square method $\overline{\ln\varphi(h_k)} = \ln f - \frac{1}{H^*}h_k + e_k$, when the series of tsunami heights is known (1), it is necessary to be able to estimate the average logarithms of frequencies $\ln\varphi(h_k)$, corresponding to the ranked tsunami heights h_k as well as their variances $D(\varphi(h_k))$ [20–22]. Here, e_k are centered random deviates. Such statistical characteristics can be obtained analytically, using the fact that the sequence of strong tsunamis is close to the Poisson's one [23]. Therefore, the probability that n tsunami will occur in some certain place during a time period T, with a run-up height above level h, is given by the formula:

$$P_n(h) = e^{-\varphi(h)} \frac{[\varphi(h) \cdot T]^n}{n!}. \qquad (4)$$

Fig. 2. South Kuril Islands.

Let us consider the cumulative distribution function $F(h_k)$ for each ranked tsunami height h_k. The situation $\{h_k \leq h\}$ is realized if the number of tsunamis with a height above the threshold h is not greater than (k–1). Then the sought probability is the sum:

$$F(h_k) = \sum_{s=0}^{k-1} P_s(h_k) = e^{-\varphi(h_k)T} \sum_{s=0}^{k-1} \frac{(\varphi(h_k)T)^s}{s!} \quad (5)$$

Here, the threshold value of a tsunami height with a number k is already designated as h_k. The derivative of $F(h_k)$ with respect to $\varphi(h_k)$ provides a probability density for the function $\varphi(h_k)$

$$\rho_\varphi(\varphi(h_k)) = e^{-\varphi(h_k)\cdot T} \frac{[\varphi(h_k)\cdot T]^{k-1}}{(k-1)!} \cdot T. \quad (6)$$

This formula shows that random variables $\varphi(h_k)$ have a gamma distribution $\Gamma(k, T)$ [20, 22], and the necessary statistical characteristics such as means and variances can be obtained analytically:

$$\varphi_k = \overline{\ln\varphi(h_k)} = \sum_{s=1}^{k-1} \frac{1}{s} - 0.577\ldots - \ln T, \quad (7)$$

$$D_k = D(\ln\varphi(h_k)) = \frac{\pi^2}{6} - \sum_{s=1}^{k-1} \frac{1}{s^2}, \quad (8)$$

$$\sigma_k = \sigma(\ln\varphi(h_k)) = \sqrt{\frac{\pi^2}{6} - \sum_{s=1}^{k-1} \frac{1}{s^2}}. \quad (9)$$

Since the values of variances D_k are different for different values of the number k, the weighted least squares method should be used [20, 22].

Tsunami height recurrence function for the Port of Malokurilskoye

Data on tsunami events are collected in catalogs of varying details and for different historical periods. Tsunami electronic catalogs available on the Internet are created [24, 25]. A significant part of these catalogs are tsunami run-up heights, which are the maximum heights of the sea level at the edge of the flood zone measured as a result of the survey. Despite the existence of such catalogs, which contain much information on a tsunami as a whole, the lack of reliable quantitative information on both weak and strong events is a major constraint to the development and testing of physically based tsunami models on the coast. Weak tsunamis occur almost annually, but they are not always reliably distinguished from other wave processes due to the small magnitude of these waves, especially in the coastal zone, and consequently, information about such tsunamis is insufficient. Only strong events are dangerous, but the lack of information about this group of events is associated with their rarity in this case.

The South Kuril Islands is one of the most seismically active parts of the Pacific periphery (Fig. 1). All earthquakes in the region with a magnitude of Mw ≥ 8 and several earthquakes with a magnitude of Mw ≥ 7.5 were accompanied by deadly tsunamis. The region was also hit by the largest tsunamis from remote sources in the Pacific, such as the events in Chile in 1960, Tohoku in 2011 and others.

Nevertheless, the lack of data on tsunami heights is also a major problem in this region with high tsunami activity. The measurements of the catastrophic tsunami of November 5, 1952, were documented in detail only for the coast of South Kamchatka and the Northern Kuril Islands. For the South Kuril region, the tsunami catalogs contain only one fact related to the 1952 tsunami event on Iturup Island, without specifying a certain location. The earlier tsunamis in the region have been sketchy documented. Therefore, 1953 was chosen as the starting year for the statistical study.

For instance, we can construct the tsunami height recurrence function for the Port of Malokurilskoye, Shikotan Island, which is based on a series of reliable data on the heights of the historical tsunamis [24, 25] (Fig. 3). For estimation of parameters f and H^* of recurrence function, we use the weighted least squares method [20–22] applied to a dataset (1) of the tsunami run-up heights for the Port of Malokurilskoye, at which quadratic residual is minimized:

$$r = \sum_{k=1}^{N} (\overline{(\ln \varphi(h_k))} - \ln f + \frac{h_k}{H^*})^2 / D_k. \quad (10)$$

Clearly, the value of the parameter ln f is given by the intersection point of the straight regression line and the ordinate axis, and the value $-1/H^*$ characterizes the slope of the regression line. It is also evident that the accuracy of the estimates of tsunami activity $f = (0.15 \pm 0.08)$ yr^{-1} and $H^* = (1.7 \pm 0.8)$ m appeared to be predictably low, since these estimates are based on the total $N = 6$ data on the tsunami run-ups with $h \geq 1.0$ m recorded over 67 years of observation (1953–2020).

Substitution of exponential approximation (3) into the expression for the cumulative distribution function (5) and subsequent differentiation with respect to h_k gives a probability density function ρ_h for h_k

$$\rho_h(h_k) = e^{-p} \cdot \frac{p^{k-1}}{(k-1)!} \cdot \frac{p}{H^*},$$
$$p = f \cdot T \cdot \exp\left(-\frac{h_k}{H^*}\right), \quad (11)$$

which, like (3), is only valid for $h_k > 0.5$ m (Fig. 4). In this case, the most likely values for the ranked tsunami heights h_k correspond to the maxima of $\rho_h(h_k)$ for each k:

$$\widehat{h_k} = H^* \ln(Tf/k), \qquad \widehat{h_k} \geq 0.5 \text{ m}. \quad (12)$$

Fig. 4 shows that the largest values of tsunami heights, especially h_1, are the least stable, the probability density plot for h_1 is very gentle, and the recurrence frequency of the maximum value h_1 is characterized by the highest standard deviation value $\sigma_1 \approx 1.28$ (Fig. 3). Therefore, the σ-tolerance range for the recurrence period of the height h_1 of the strongest event, corresponding to the standard deviation σ_1, is extremely large ($T/3.6 - 3.6 \cdot T$), where T is real observation period and $\exp(\sigma_1) \approx 3.6$. This means, for example, that the maximum value of the tsunami height recorded at some location over the 30-year observation period should be associated with a wide range of possible recurrence periods of about 10 to 100 years in accordance with the standard deviation $\sigma_1 = 1.28$. As the number k increases, the values of standard deviations σ_k slowly decrease and the distribution plots $\rho_h(h_k)$ become more acute, which indicates an increase in the stability of the tsunami heights h_k with large numbers k in the series (1).

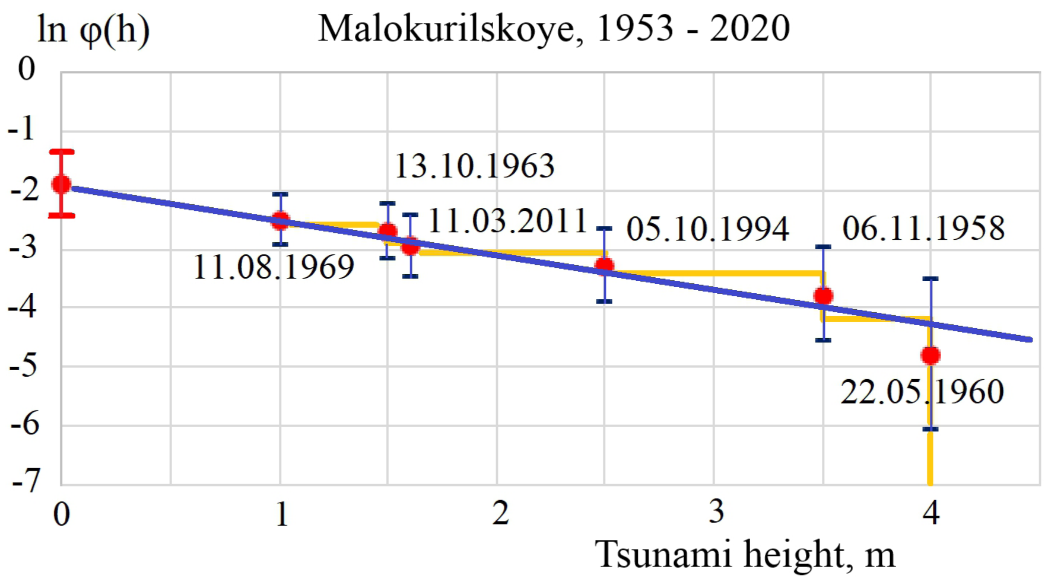

Fig. 3. Empirical tsunami recurrence step function for the Port of Malokurilskoye constructed using the historical tsunami heights with $h \geq 1.0$ m during the period of 1953–2020 (yellow stepped line), and its approximation by the regression straight line, obtained using the weighted least squares method (blue line). All the values $\overline{\ln \varphi(h_k)}$ (marked by the red circles) are associated with the corresponding standard deviations σ_k (9). Asymptotic frequency of large tsunamis for the Port of Malokurilskoye is $f = (0.15 \pm 0.08)$ yr^{-1}, and its position is marked by the red circle in the ordinate axis. The characteristic tsunami height in the Port of Malokurilskoye is $H^* = (1.7 \pm 0.8)$ m and $1/H^* = (0.6 \pm 0.3)$ m^{-1}.

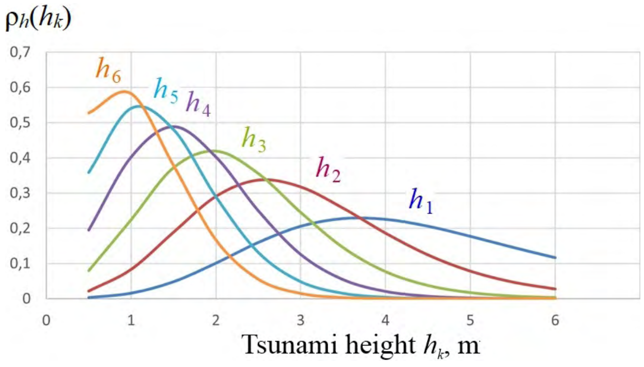

Fig. 4. Probability density functions of the ranked tsunami heights h_k (11) for the Port of Malokurilskoye for the observation period $T = 67$ years and $k = 1, \ldots, 6$.

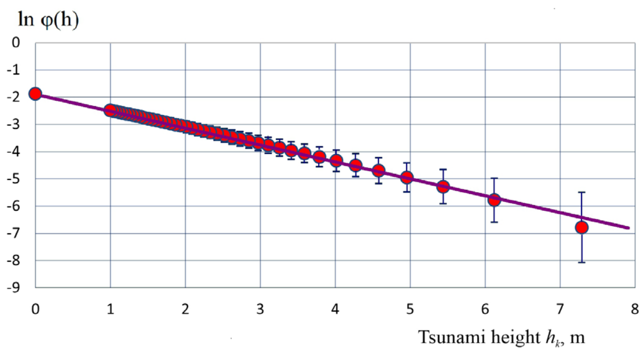

Fig. 5. Synthetic recurrence function of tsunami heights for the Port of Malokurilskoye for a period of 500 years, 42 events with $h \geq 1.0$ m. All the most probable values of tsunami heights (red circles) are associated with the corresponding standard deviations σ_k (9).

Tsunami height synthetic catalog and the estimates of the accuracy of the tsunami activity parameters

The opposite situation can be considered: we can use the parameters $f_0 = 0.15$ yr^{-1} and $H_0^* = 1.7$ m for the Port of Malokurilskoye as input data and construct the synthetic series of the most likely tsunami heights $\widehat{h_k}$, $\widehat{h_k} \geq 1.0$ m (12) for a given time period, for example, $T = 250$ and 500 yr (Fig. 5), and use them to estimate the "output parameters" f and H^* and their variances, as it was performed for the estimation of the tsunami activity parameters on the basis of real data (Fig. 3).

As a result, the following estimates were obtained: $f = (0.15 \pm 0.01)$ yr^{-1} and $H^* = (1.7 \pm 0.16)$ m for T = 250 yr and $f = (0.15 \pm 0.006)$ yr^{-1} and $H^* = (1.7 \pm 0.08)$ m for $T = 500$ yr. Thus, the complete series of tsunami heights in a given location with a duration of at least 250 or 500 years are required to obtain the tsunami activity parameters with an acceptable accuracy of 10 or 5 % [17].

The task of obtaining a general theoretical result within the framework of the same technology is much more interesting, since this approach allows tracing the evident dependence of the variance of the tsunami activity parameters f and H^* on the observation period duration T, the amount of the used data N, as well as on real but a priori unknown parameters of tsunami activity f_0 и H_0^*.

Let some point of some coast be characterized by the tsunami activity parameters f_0 и H_0^* (without specifying their values). Formally, we can construct a synthetic series of tsunami heights at a given location, taking as ranked values of tsunami heights h_k their most probable values $\widehat{h_k} = H_0^* \ln(Tf_0/k)$, which clearly depend on the given tsunami activity parameters f_0 и H_0^* and the observation period T. Consequently, according to the formal series of ranked tsunami heights $\{\widehat{h_k}\}$, we can estimate the values of the tsunami activity parameters f and H^* and their variances by minimizing the corresponding quadratic residual.

$$r = \sum_{k=1}^{N} (\varphi_k - \ln f + \frac{1}{H^*} H_0^* \ln(Tf_0/k))^2 / D_k. \quad (13)$$

Setting equal to zero the derivatives of the residual (13) with respect to the desired parameters f and H^* brings to the linear system of equations 2×2 in the form of $AX = Y$ [20–22], where

$$A = \begin{pmatrix} \sum_1^N \frac{1}{D_k} & -\sum_1^N \frac{\widehat{h_k}}{D_k} \\ -\sum_1^N \frac{\widehat{h_k}}{D_k} & \sum_1^N \frac{\widehat{h_k}^2}{D_k} \end{pmatrix}, \quad X = \begin{pmatrix} \ln f \\ 1/H^* \end{pmatrix}, \quad (14)$$

$$Y = \begin{pmatrix} \sum_1^N \frac{\varphi_k}{D_k} \\ \sum_1^N \frac{\varphi_k \cdot \widehat{h_k}}{D_k} \end{pmatrix}.$$

The determinant of the system depends only on the number of data N and is proportional to the square of H_0^*:

$$\Delta = (H_0^*)^2 \left(\sum_{k=1}^{N} \frac{1}{D_k} \cdot \sum_{k=1}^{N} \frac{(\ln k)^2}{D_k} - \left(\sum_{k=1}^{N} \frac{\ln k}{D_k} \right)^2 \right) =$$

$$= (H_0^*)^2 \cdot \Delta_1(N) \quad (15)$$

The inverse matrix A^{-1} is the covariance matrix

$$A^{-1} = \frac{1}{\Delta} \begin{pmatrix} \sum_{k=1}^{N} \frac{\widehat{h_k}^2}{D_k} & \sum_{k=1}^{N} \frac{\widehat{h_k}}{D_k} \\ \sum_{k=1}^{N} \frac{\widehat{h_k}}{D_k} & \sum_{k=1}^{N} \frac{1}{D_k} \end{pmatrix}. \quad (16)$$

Consequently, the variances of the estimates of the tsunami activity parameters $\ln f$ and $1/H^*$ are given by the diagonal elements of the matrix A^{-1} [20–22]:

$$D(\ln f) = \frac{1}{\Delta_1} \left[(\ln Tf_0)^2 \sum_{1}^{N} \frac{1}{D_k} - 2(\ln Tf_0) \cdot \sum_{1}^{N} \frac{\ln k}{D_k} + \right.$$

$$\left. + \sum_{1}^{N} \frac{(\ln k)^2}{D_k} \right], \quad (17)$$

$$D\left(\frac{1}{H^*}\right) = \frac{1}{{H_0}^{*2} \cdot \Delta_1(N)} \sum_{1}^{N} \frac{1}{D_k}. \quad (18)$$

Formulas (17, 18) are universal in the sense that they describe the dependence of the variances of the tsunami activity parameters $D(\ln f)$ and $D(H^{*-1})$ on a priori unknown values of the tsunami activity parameters f_0 and H_0^* and the amount of used data N.

The final series, included in formulas (17) and (18), have a convenient numerical approximation for large values of the amount of used data $N > 100$ (Fig. 6):

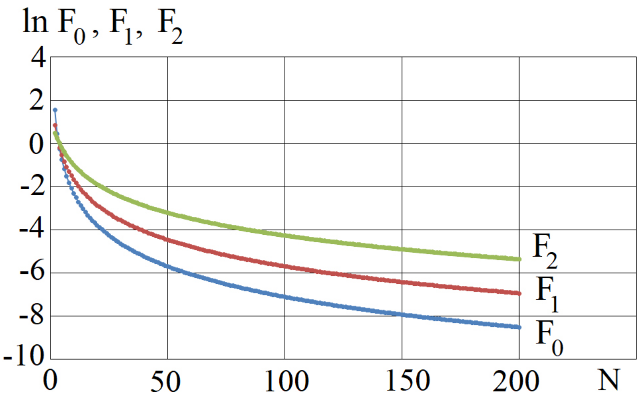

Fig. 6. Plots of the functions $F_0(N)$, $F_1(N)$ and $F_2(N)$ (19–21).

$$F_0(N) = \frac{1}{\Delta_1} \sum_{1}^{N} \frac{1}{D_k} \approx 8.2N^{-2}, \quad (19)$$

$$F_1(N) = \frac{1}{\Delta_1} \sum_{1}^{N} \frac{\ln k}{D_k} \approx 12.3N^{-1.78}, \quad (20)$$

$$F_2(N) = \frac{1}{\Delta_1} \sum_{1}^{N} \frac{(\ln k)^2}{D_k} \approx 17.8N^{-1.55}. \quad (21)$$

According to formulas (18, 19), the variance of the inverse value of the characteristic height $D(H^{*-1})$ depends on the amount of used data N through the function $F_0(N)$ and on the parameter H_0^{*-2}. Formula (17) for the variance of the logarithm of the strong tsunami frequency $D(\ln f)$ demonstrates a more complex dependence both on the number of data N and on the parameter f_0 and on the duration of the observation period T. However, since the function $F_2(N)$ decreases much more slowly than the functions $F_0(N)$ and $F_1(N)$ (Fig. 6), this "nullifies" the dependence of the variance $D(\ln f)$ on the parameters f_0 and T for the large values of the amount of data N.

The limitation on the height of the tsunami wave $h > 0.5$ m for the validity of the exponential approximation (3) of the tsunami recurrence function (2) leads to limitations on the amount of data N that can be correctly used in statistical conclusions depending on the tsunami activity parameters f and H^* and on the duration of observations T:

$$\ln N \leq \ln Tf - 0.5 \text{ m} / H^*. \quad (22)$$

Conclusion

The development of the coasts and coastal urban development in the tsunami hazardous regions has stimulated the progress in both purely scientific works on the physics of tsunami and applied works on the creation of such a popular product as the tsunami zoning maps. In turn, the problem of estimating the accuracy of the tsunami activity and, consequently, the tsunami hazard, is revealed when the maps creating, and this problem is mainly due to the lack of reliable information on the tsunami manifestation features.

For example, the synthetic tsunami height catalogs, constructed for the Port of Malokurilskoye, have shown that the complete (without gaps) series of tsunami heights in a given location lasting at least 250 or 500 years are necessary to obtain the tsunami activity parameters with an acceptable accuracy of 10 % or 5 %. In fact, existing catalogs contain the centuries-long tsunami data series for the northeast coast of Honshu and the Pacific coast of South America, but these descriptions contain only the strongest events with gaps, so that datasets (1) are not complete for these coasts either.

Formally, the datasets for several millennia can be obtained from the analysis of palaeotsunami data, but the actual use of such data for estimating the tsunami activity associated with a number of serious problems, such as the identification of palaeotsunami deposits, their dating, quantitative accounting of preservation, etc.

On the basis of probability density functions plots of the ranked tsunami heights constructed for the Port of Malokurilskoye, the explanation of weak statistical stability of large values of the tsunami heights, especially the largest one in a series of observations, is given. In particular, this means, for example, that the maximum value of the tsunami height recorded at some location during the 30-year observation period should be associated with a wide range of possible recurrence periods of about 10 to 100 years.

In general, the theoretical development of a probabilistic model describing the dynamics of the tsunami sequence of the Poisson's type, made it possible to obtain universal analytical formulas for the variances of the tsunami activity parameters, characterizing their accuracy depending on the amount of data used and the duration of observations. These analytical formulas are the solution to the problem of accuracy only for the simplest, ideal case, when there is a complete series of tsunami heights without gaps recorded in a single place over a long observation period. It is unclear, whether it is possible to obtain an analytical solution (or only a numerical one) for the group of the tsunami observation points. Nevertheless, the formulas obtained should be considered as progress in solving the problem of estimating the accuracy of the tsunami activity parameters, as they made the problem to be concretized and numerically assessed the lack of currently available information on the such complex phenomenon as a tsunami.

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