A tsunami hazard parameter for Zhupanovo, Kamchatka, calculated using historical and paleotsunami data

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Abstract. The tsunami hazard for the Kamchatka peninsula coast can be estimated using historical data from catalogues, but the dispersion of found parameters is rather large because of the small number of good tsunami data. This situation can be considerably improved using paleotsunami data. The relative a priori error of characteristic tsunami height H^* for Zhupanovo created from its standard deviation is equal to 0.6 for a model based on three historical data sets for Zhupanovo with tsunami height more then 0.5 m. Adding about 40 paleotsunami data sets makes the relative a priori error equal to 0.2.

1. Probability Model for Tsunami Run-Up

It is known (Gaisky, 1970; Lomnitz, 1986) that a sequence of earthquakes exceeding a chosen magnitude threshold differs little from the Poissonian sequence. Deviations from the Poissonian type are related to aftershocks which are not tsunamigenic, as a rule. According to this, the sequence of tsunamis occurring at each point with maximal run-up height exceeding a chosen threshold can be considered as the Poissonian flow. So, the probability that there will be n tsunamis with height more than h_0 at the chosen point is given by the formula (Kaistrenko, 1989):

$$P_n(h \geq h_0) = \frac{[\varphi(h_0) \cdot T]^n}{n!} \cdot e^{-\varphi(h_0) \cdot T} \tag{1}$$

where T is the observing time interval, and $\varphi(h_0)$ is the mean frequency of tsunamis with height more than elected "threshold" h_0. The last function is named the recurrence function. The asymptotic of the tsunami recurrence function for extreme tsunami heights should be in accordance with well known extreme statistics. The last one explains the use of exponential approximation for an empirical recurrence function,

$$\varphi(h) = f(x) \cdot e^{-\frac{h}{H^*(x)}}, \tag{2}$$

which is in accordance with a double negative exponential law for extreme values (Galambos, 1978). Parameter H^* is the calibrated (characteristic) tsunami height dependent on the coastal point x of tsunami observation, and f is tsunami frequency. The last parameter is a regional one, that varies quite slowly along the Pacific coast (Go *et al.*, 1988; Chung *et al.*, 1993), and can be considered as a constant value for all points of the region,

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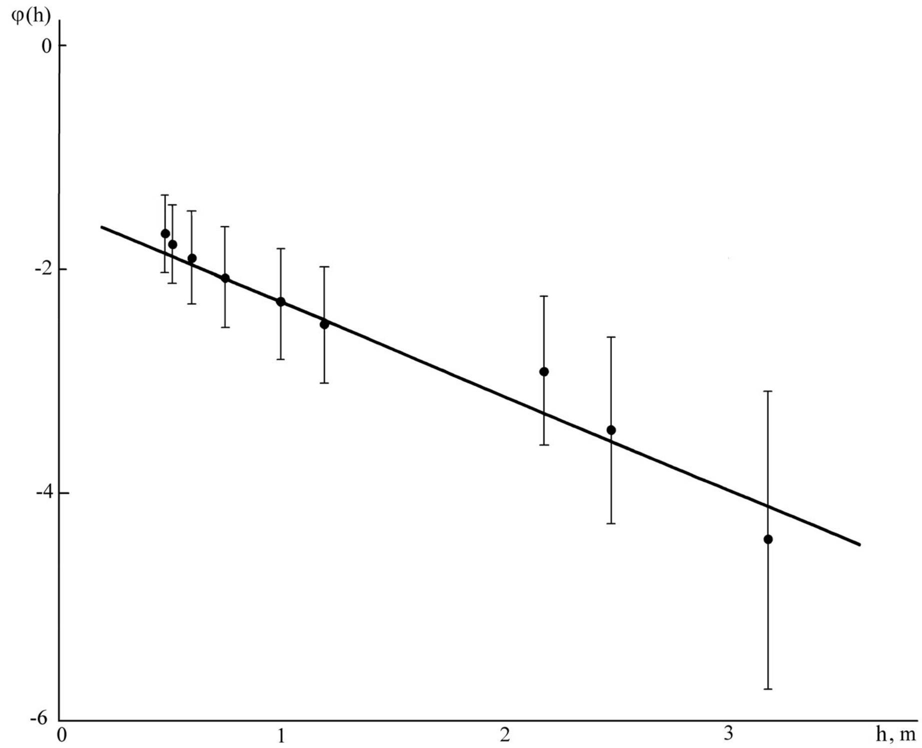

Figure 1: Empirical recurrence function for Yuzhno-Kurilsk with a priori errors based on tsunami data with height >0.5 m for time period 1952–1998, $n = 9$.

for example, at Southern Kamchatka. The exponential approximation for the tsunami recurrence function was used by Wiegel (1965) originally for tsunami hazard estimation for the California coast.

Practically, the functions $\varphi(h_0)$ are decrypted by the tables, and the tables often do not contain enough data. The weighted least square method (Hudson, 1964) allows us to estimate the tsunami activity parameters H^* and f.

Let the tsunami heights recorded at a point x be ordered $h1 > h2 > h3\ldots$ according to its value. Then the average tsunami frequency related to the ordered tsunami heights h_k and its dispersions are given by the formulae (Kaistrenko, 1989):

$$\begin{aligned} \overline{\ln\varphi(h_k)} &= \sum_{s=1}^{k-1}\frac{1}{s} - 0.577\ldots - \ln T, \\ D(\ln\varphi(h_k)) &= \frac{\pi^2}{6} - \sum_{s=1}^{k-1}\frac{1}{s^2}. \end{aligned} \tag{3}$$

Using the weighted least squares method with these formulae the parameters H^* and f of the empirical recurrence function can be estimated with their dispersions (a priori errors). Using the usual least squares method is not correct because the values $\ln \varphi(h_k)$ are dependent stochastically and their dispersions are different. The logarithm of the tsunami recurrence function for maximal tsunami height h_1 has a maximal dispersion. It means that maximal tsunami height is not a stable parameter and all tsunami heights h_k with large numbers k are stable because the dispersion related to it, $D(\ln \varphi(h_k))$, is a decreasing function of numbers k. This explains the benefit of using the paleotsunami data: more data reduces the dispersion of tsunami activity parameters H^* and f. The standard deviations $\sigma = \sqrt{D(\ln \varphi(h_k))}$ can be considered as an a priori error of the tsunami recurrence function in logarithmic scale.

Having parameters H^* and f for any coastal point x, the average tsunami height h_T with recurrence period T can be calculated as

$$h_T = H^* \cdot \ln(T \cdot f) \tag{4}$$

The distribution of this parameter along the coast calculated using the natural data from catalogues can be used to create the tsunami hazard maps.

2. An Example of Empirical Recurrence Function

All the sets of historical data for the Kamchatka coast are short and not good enough to create the recurrence function. On the contrary, several sets of historical data for the Southern Kuril Islands are good enough. For example, the set for Yuzhno-Kurilsk contains nine tsunami data sets with maximal tsunami height more than 0.5 m and can be used to create the empirical tsunami recurrence function (Fig. 1) and calculate parameters H^* and f.

These parameters and the standard deviations $\sigma = \sqrt{D}$ calculated by the weighted least squares method are the following: $H^* = 1.2$ m, $\sigma(1/H^*) = 0.26$ 1/m, $f = 0.28$ 1/year, $\sigma(\ln f) = 0.3$.

The product $\sigma(1/H^*) \cdot H^* \approx \sigma(H^*)/H^*$ can be considered as the relative a priori error for calibrating the tsunami height H^*, and the value $\sigma(\ln(f)) \approx \sigma(f)/f$ can be considered as the relative a priori error for tsunami frequency f. These parameters are 0.3 and 0.3.

Tsunami frequency f should be a stable parameter and its relative a priori error $\sigma(\ln f)$ can be an indicator of the data set quality. The dependence of the a priori error of tsunami frequency f on the number of tsunami data starting from the maximal one is shown in Fig. 2. The result of this picture is the following: a tsunami data set can be considered good enough if it contains more than five data sets.

3. An Empirical Recurrence Function for Zhupanovo, Kamchatka

Tsunami catalogues contain only three reliable tsunami heights during the last 50 years: 5 m (1952), 4 m (1960) and 0.5 m (1997). The parameters H^* and f and its standard deviations calculated by the weighted least squares

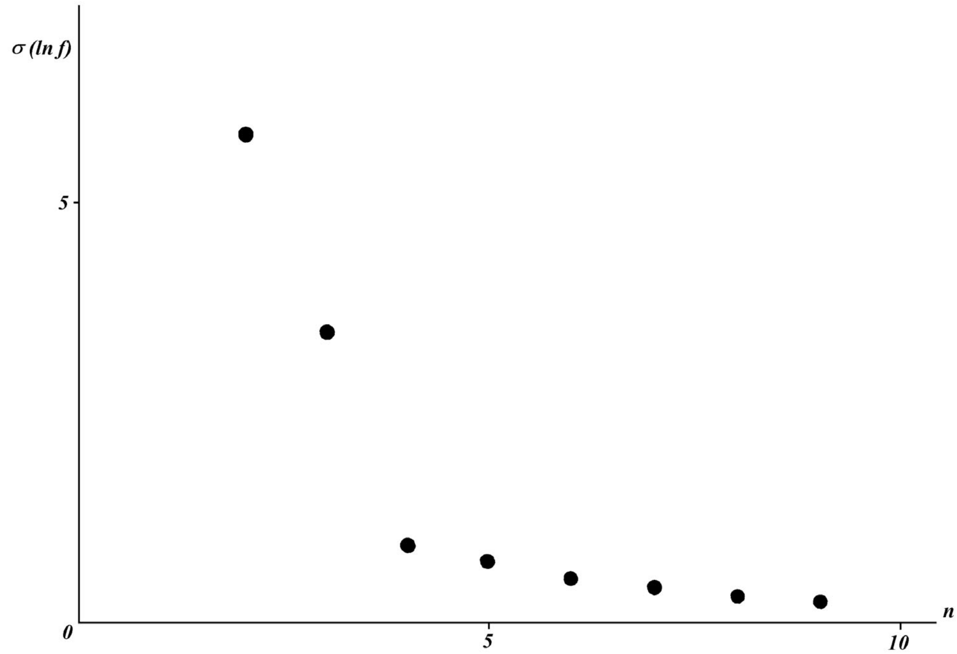

Figure 2: The relationship between a priori error of tsunami frequency f and number of tsunami data n.

method are the following: $H^* = 4.4$ m, $\sigma(1/H^*) = 0.2$ 1/m, relative error $\sigma(H^*)/H^* \approx 1.1$, $f = 0.06$ 1/year, $\sigma(\ln f) = 0.7$. These estimations cannot be considered as good enough. This situation can be improved slightly by using the historical data for neighboring points because the tsunami frequency f for them should be the same ($f = 0.07$ 1/year with relative a priori error 0.2 and characteristic tsunami height $H^* = 3.9$ m with relative a priori error 0.6).

During 2 years (1995–1996) the investigation of tsunami deposits on the coast of Kronotsky gulf were performed (Pinegina *et al.*, 2000). About 40 layers related to tsunamis were found near Zhupanovo point on terraces with different height over the sea level (5, 10, 15, and 30 m). All the historical and paleotsunami data are shown in Fig. 3 with their a priori errors of logarithm of corresponding tsunami frequency. A large number of established paleotsunamis makes the a priori errors much less. Using the additional paleotsunami data we received other values for parameters H^* and f and its standard deviations: $H^* = 8.3$ m, relative error $\sigma(H^*)/H^* \approx 0.2$, $f = 0.2$ 1/year, $\sigma(\ln f) = 0.3$.

4. Conclusions

The difference between the parameters received with and without paleotsunami data seems essential and should be explained. There are several explanations. At first, the tsunami sequence is not a homogeneous process for the time period of about several thousand years. The second explanation

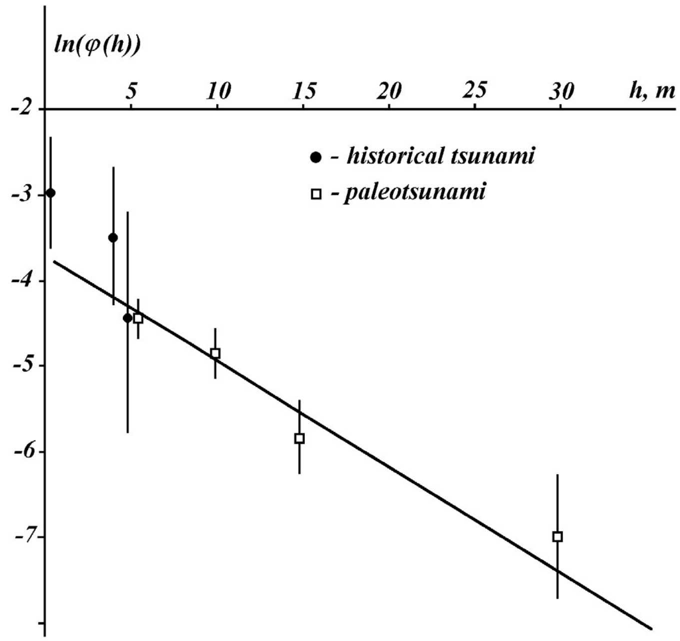

Figure 3: Empirical recurrence function for Zhupanovo, Kamchatka based on historical and paleotsunami data.

is the "erasing" of old tsunami traces by different processes. In this case the difference can be related to paleotsunamis with disappeared traces.

It is impossible to give a single explanation using the data for a single point, and it is possible to do so later after using a combination of historical and paleotsunami data for several points.

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