A new paradigm of tsunami safety solution

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Abstract. The authors present a new complex approach and a system solution to provide safe and sustainable development of tsunami-prone exploited coastal and shelf areas. The intended working set consists of the following components:

1. Design independent and dependent criteria of tsunami hazard;
2. Tsunami hazard zoning maps and tables for tsunami-prone coasts using design criteria;
3. Manuals for tsunami load formations and for tsunami resistance evaluation of different types of construction;
4. Acceptable tsunami risk criteria determination;
5. Land-use rules and construction code;
6. Tsunami disaster damage scenarios technique;
7. Standard tsunami risk reduction measures both to reduce the tsunami impact on the existing marine constructions (or urban areas) and to mitigate the tsunami disaster by means of new codes and rules.

The authors offer to discuss this developed integrated approach and risk management solutions as a new paradigm for acceptance and implementation by each tsunami-prone community.

The article presented here contains tsunami hazard scores for the Russian Pacific, examples of estimation of interaction of long waves with a vertical wall and cylinder, and a new tsunami safety paradigm, as a whole.

1. Introduction

A tsunami is a dangerous natural phenomenon generating a wave process in the ocean usually induced by a strong submarine earthquake. It is well known that the Russian Far Eastern coast is one of the most tectonically active margins of the Pacific with frequent tsunami occurrences. After a catastrophic tsunami in November 1952 that destroyed the greater part of Severo-Kurilsk, more than 40 tsunamis have been recorded on the Far East coast of Russia, the height being more than 5 m in seven cases; and in 1952, 1963, 1969, and 1994 the wave heights were up to 15 m in some places.

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The current Tsunami Preparedness Policy, oriented toward warning and evacuation, needs to be revised worldwide.

Coastal cities, ports, and marine constructions at tsunami risk are growing and becoming more and more vulnerable to a tsunami impact. Today we cannot ignore an increasing risk of cessation of sea-port operation, oil platform destruction, or coastal devastation.

The safe and stable function of sea ports, coastal oil or gas tanks, cold storage, fisheries, and other facilities become more significant for the economic development of coastal communities.

Economic risk management is an important goal which has to be solved for coastal urban and industrial areas at tsunami risk.

For example, the Russia Governmental Decree #10 of 8 January 1964 forbids any construction in tsunami-prone zones. This decree, which obstructs normal economic development, has been often violated (contravened), and tsunami impact has not been taken into account when coastal structures are designed. Thus, during the last 35 years on the Russia Pacific Coast a lot of structures vulnerable to tsunamis were created.

A previous attempt to carry out a tsunami construction code was undertaken by Mark Klyachko in 1988. This projected document was included in the 1990s Plan of Gosstroy of the USSR. However, this code has not been developed due to a variety of reasons.

Now, after the IDNDR ending we are coming back to tsunami construction code problems on another, higher level of knowledge and experience.

2. Background and Objectives

Recent earthquake, tsunami, and hurricane disasters clearly demonstrate an extremely high vulnerability for great damage of marine structures and other special facilities on the coast. Average estimates of probable economic damage from tsunamis in a modern seaport can reach $50 billion.

Existing sea coast structures are very vulnerable to a tsunami impact, but we still ignore an economic tsunami risk. By doing so, we don't really know the tsunami risk estimations on any particular coastal area. Such a state of affairs conflicts with sustainable development needs.

Decision-makers must understand what can happen if a tsunami occurs, and they have to reduce the probability of loss and damage to minimize the risk before a disaster strikes.

To solve this multidisciplinary problem we collect a target team, combining together the efforts of academics and engineers: oceanologists, geophysicists, hydrotechnical experts, risk analysis experts, etc.

The objective of this research is to briefly present a new complex approach and a system solution to provide safe and sustainable development of tsunami-prone exploited coastal and shelf areas which consist of:

1. Design independent and dependent criteria of tsunami hazard, viz.:
    - head wave height,
    - head wave velocity (or length),

- event probability,
- run-up—the only dependent criterion which has to be refined under tsunami microzonation and to be taken into consideration when planning land-use, insurance, and evacuation.

2. Tsunami hazard zonation maps and tables for tsunami-prone coasts using design criteria;
3. Manuals for tsunami load formations and for tsunami resistance evaluation of different types of construction,
4. Acceptable tsunami risk criteria determination,
5. Land-use rules and construction codes;
6. Tsunami disaster damage scenario techniques;
7. Standard tsunami risk reduction measures both to reduce the tsunami impact on the existing marine constructions (or urban areas) and to mitigate the tsunami disaster.

3. A Quantitative Estimation of Tsunami Hazard and the Tsunami Zoning Scheme of the Russian Pacific Coast

The classification of the Russian Pacific coast according to the degree of tsunami hazard is the main practical problem. The first projects to solve this problem were performed in the 1960s in the former USSR (Ikonnikova, 1963). Later they were improved (Atlas of Maximum Run-up, 1978; Pelinovsky and Plink, 1980). All of them were based on calculations of tsunami propagation from model sources according to a seismological representation of source at this time, and did not use direct natural tsunami data. Lately the evaluation of stable characteristics of tsunami occurrences on the coast has become a basis for a new approach. In contrast to previous ones, this new approach took into account the time factor and gave the tsunami run-up level forecast h_T with recurrence period T. Based on the Poisson character of tsunami sequences produced by Poisson sequences of strong underwater earthquakes (Gaisky, 1970; Lomnitz, 1986), the parameter h_T can be given by the formula (Kaistrenko, 1989)

$$h_T = H^* \cdot \ln(T \cdot f). \qquad (1)$$

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

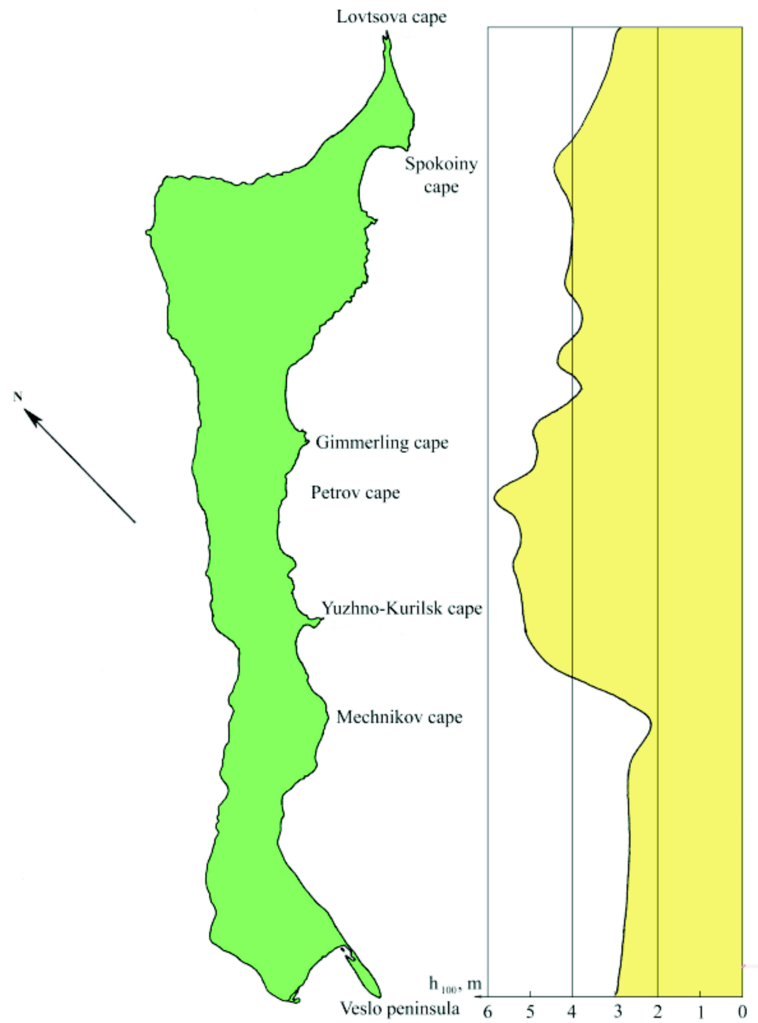

Figure 1: Detailed distribution of parameter h_{100} along the Kunashir Island coast.

The distribution of these parameters along the coast calculated using the natural data from catalogues can be used to create tsunami hazard maps like the one for Kunashir Island (see Fig. 1).

According to the analytical theory of wave run-up (Kaistrenko *et al.*, 1993) the wave behavior depends on the dimensionless parameter

$$Br = \frac{R\omega^2}{g\alpha^2}, \tag{2}$$

where R is maximal tsunami run-up, $\omega = 2\pi/\tau$ is the wave frequency, τ is wave period, g is gravitational acceleration, and α is a slope parameter. Tsunami is a breaking wave if $Br > 1$, and it is a smooth wave-like tide if $Br < 1$.

Using h_T instead of R we can evaluate the type of forecasting tsunami run-up as a Br_T. According to the tsunami data in catalogues (Solovjev and Go, 1974, 1975; Soloviev *et al.*, 1986) most of the tsunamis in the Kuril–Kamchatka region (90% of cases) occur as smooth inundations with $Br < 1$. This parameter takes the highest value on the shores of the Second Kuril Strait, $Br_{100} \approx 2$ for tsunami recurrence period $T = 100$ years, thus explaining the extremely destructive effect of a tsunami wave in 1952 with a vertical front in the Severo–Kurilsk region.

Maximal flow velocity u_T by tsunami recurrence period T can be estimated by formula:

$$u_T = \frac{\omega h_T}{\alpha}. \tag{3}$$

This maximum of flow velocity is reached on the distance $x = (h_T/\alpha)(Br/2)$ from the shoreline in the sea direction.

4. Interaction of Long Waves with a Barrier as a Vertical Wall

The analysis of work on the interaction of long waves with a continuous barrier shows that the vertical wall problem has been fully investigated. The analytical and numerical solutions are known, and the physical and numerical experiments are performed.

In Shokhin (1979) the influence of a solitary wave on a wall was considered on the basis of the numerical decision of the Navier-Stokes equations by using the method of markers on a grid. In Su and Gardner (1969) the solution of the problem for ideal fluid was approached by applying an asymptotic of decomposition of the various orders. Mirchina (1984) used Riman-invariants to reception of dependencies to account for run-up of waves on a wall. In Aleshkov (1990) the problem of standing waves was solved with the help of a method of small parameter. The numerical solution to the problem on the basis of a method using Fourier transformation on coordinates and certainly difference the circuit on time, is found in Fenton (1982).

The character and basic features of the process of interaction of solitary waves with a vertical wall are satisfactorily described by the nonlinear-dispersive equation approach (Su, 1969; Haugel, 1981). Based on the Gorkiy University approach, the following solution for amplitude and depth averaged particle velocity is obtained:

$$\begin{aligned}(hU)_t + \left(hU^2 + \frac{gh^2}{2} - \frac{h^3}{3}R - \frac{h^2}{3}Q\right)_x \\ = d_x\left(gh - \frac{h^2}{2}R - hQ\right) - C_f U|U|,\end{aligned} \tag{4}$$

$$h_t + (hU)_x = 0, \tag{5}$$

where $R = U_{xt} + UU_{xx} - U_x^2$, $Q = (U_t + UU_x)d_x + U^2 d_{xx}$, $h = d + \eta$, d is depths of a fluid, and C_f is the factor of ground friction.

Table 1: Example of the maximal run-up values on a vertical wall.

	h/d						
The methods (authors)	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**
Experiment (Nudner)	0.20	0.40	0.63	0.86	1.12	1.43	1.8
Experiment (VNIIG)	0.16	0.38	0.64	0.87	1.1	1.4	1.8
On linearity theory	0.2	0.4	0.6	0.8	1.0	1.2	1.4
Calculated on nonlinearity theory (Mirchina)	0.2	0.4	0.64	0.88	1.12	1.36	1.6
Calculated under the theory of a solitary wave of the second approximation (Fenton)	0.2	0.42	0.64	0.92	1.26	—	—
Calculation (Gorkiy University)	0.2	0.43	0.66	0.90	1.15	1.42	1.71
Calculation (Camfield)	0.2	0.44	0.7	1.0	1.28	1.62	2.0

For the solution of problem (4)–(5) the boundary conditions were used

$$U = 0, \ \eta_x = 0, \ U_{xx} = 0, \ \text{at } x = L. \tag{6}$$

For practice the important characteristics of a wave flow influencing a structure are amplitude at a barrier, and the speed and force parameters of waves. To rate quantitatively and to choose the best solution for practical applications, a comparison was done of experiment and theoretical data of amplitude and pressure at a wall. Examples of maximal run-up values of waves on a vertical wall referred to depth of water at a wall (d) are given in Table 1 depending on the relative height of an initial wave (h/d).

The comparisons have shown that the values of the hydrodynamic characteristics determined on the basis of the solutions of (4)–(6) will be quite coordinated to the data of experiments in the field of relative heights of waves $0 \leq h/d \leq 0.5$. These solutions are based on the developed engineering formula of influences of long waves on vertical structures.

Results of research on the maximal run-up of a wave on a wall, the horizontal force and moment, are approximated by the following dependencies:

$$\begin{aligned} \eta_{\max}/d &= 1.99a + 0.602a^2 + 0.039a^3; \\ F/\rho d^2 &= 2.26a - 0.602a^2 + 0.829a^3; \\ M/\rho d^3 &= 1.29a - 0.69a^2 + 0.3529a^3, \end{aligned}$$

where $a = h/d$ and ρ is the density of water.

5. Interaction of Long Waves with Vertical Cylindrical Barrier

Research on the interaction of a wave flow with a cylinder shows that the process of a flow can occur in two regimes. The first regime takes place when the size of a barrier is much less than the length of a wave. Such conditions flows the basic contribution to total loading bring in forces arising as a result of education and failure of whirl waters from a surface of a barrier. In this case maximal loading from waves will be determined under the formula

$$Q = C_x \frac{\rho U|U|}{2} S, \tag{7}$$

where

- U is the horizontal component of speed of particles in the wave flow, not indignant of a barrier,
- ρ is the density of water,
- S is the middle area of a section,
- C_x is the drag coefficient.

The second regime is characteristic of a barrier whose dimensions are comparable to the length of a wave. The basic role in definition of loading here play diffractional effects, and wave loadings can be found by a calculational-theoretical method.

Another case is also possible when the contribution of both regimes of the flow to the value of wave loading is comparable among themselves. For example, in the case of the action of wind waves on a vertical cylinder, loading will be determined by the formula containing inertial and drag components. In the case of the action of long waves, in particular, tsunami waves, the barrier also can be subjected to the conditions of both flow regimes. In the first case, the inertial component of loading was much less drag and can be neglected. In the second case loading is determined only by the inertial member.

For an evaluation of loadings from tsunami waves on a barrier of the small cross sizes the experimental research are carried out and the comparisons of parameters of a wave flow to result of accounts on dependencies are performed using Boussinesq, McCowan, and Laitone formulas. The comparisons have shown that the values of speed (U) determined on the formulas Boussinesq better correspond to the experimental data.

The analysis of experimental data of drag coefficient has shown that a flow of the cylinder by the solitary wave of value C_x it is possible to accept the same conditions as in case of short (wind) waves.

By consideration of the problem about action of the solitary wave on a vertical barrier of the large diameter there is an associated feature that the length of the solitary wave aspires to infinity, and parameter $kD/2$ determining the area of applicability of the diffraction theory aspires to zero. Thus, it is possible to appear beyond the framework of applicability of the diffraction theory ($ka < 0.2\pi,\ a = D/2$) even in that case, when the diffraction interaction prevails. Therefore, for a rating of the regime of a flow enter parameter $\sqrt{ha^2/d^3}$, where h is the height of a wave, a is the radius of a cylinder, and d is the depth of water.

De St. Q. Isaacson (1983) agrees that under conditions $\sqrt{ha^2/d^3} \geq 0.36$ and $ka > 0.2\pi$ in problems of interaction of the solitary wave with a barrier, the diffraction theory is applicable. The results of work by Camfield

(1969), de St. Q. Isaacson (1983), and Belov (1985) are based on a settlement method. The problem of the diffraction of long waves on the vertical cylinder is reduced to the solution of the wave equation (Camfield, 1969; Isaacson, 1983; Belov, 1985)

$$\Delta\psi - \psi_{tt} = 0 \tag{8}$$

under boundary conditions

$$\begin{aligned} &\frac{\partial}{\partial r}(\chi + \psi) = 0,\ r = a; \\ &\psi \longrightarrow 0,\ r \longrightarrow \infty. \end{aligned} \tag{9}$$

Here ψ is the required function describing the diffraction field, χ is a function describing an initial wave, and r is the radius-vector of a considered point.

To find the solution of the problem, the function χ is represented as a Fourier series; the function ψ is found in the same manner.

After substituting these expressions in the equation and boundary conditions we find the problem for each harmonic of the Fourier series. The solution of each problem is by a method of division variables.

Loading from solitary waves on a barrier of large diameter is defined by the formula

$$Q = 0.5k\rho ghdD, \tag{10}$$

where k depends on parameters $\sqrt{hD^2/4D^3}$ and d/D (Fig. 2).

6. Conclusions

- A new paradigm, modern conception, and comprehensive approach to tsunami risk assessment and management are presented.
- A coastal human community, especially in a developing country, cannot ignore the probable damage and economic loss in cities at tsunami risk.
- To provide for tsunami risk understanding and awareness from the point of view of sustainable development of the coastal urbanizations, we have to elaborate special land-use regulations, city planning norms, and construction codes for both existing structures and new construction.
- A step-by-step solution for devising such regulations is shown in this article.

Of course, the Pacific is the most tsunami prone area in the world. However, from the point of view of economic risk, we have to extend the intended tsunami risk approach to other seas, which are located in the seismic-prone zones but do not need research from the standpoint of human loss prevention measures. Such inner seas as the Caspian, Baikal Lake, and the Great Lakes have to be considered as tsunami (seiche)-prone zones from the point of view of economic sustainability.

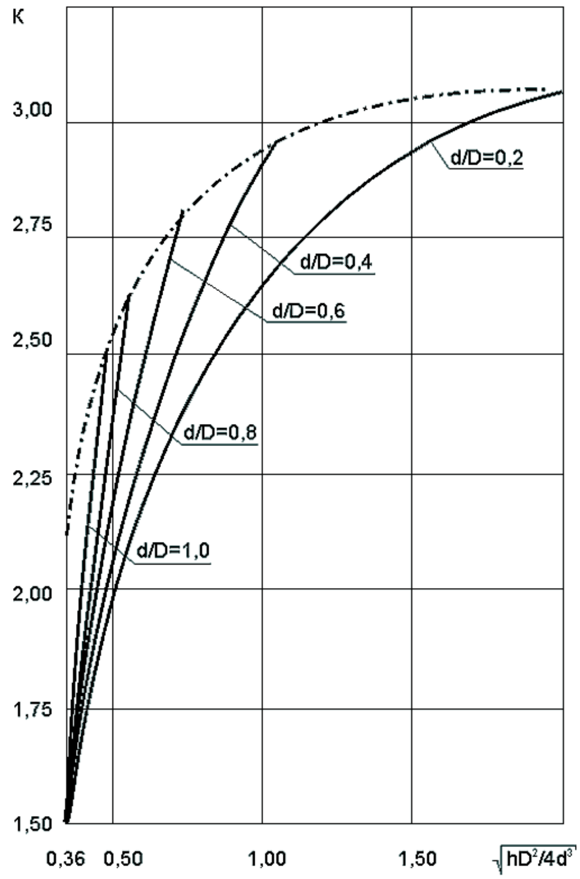

Figure 2: Experimental research has confirmed the legitimacy of the formula for account of loading.

- The tsunami hazard maps for the Russian Pacific are developed as a first edition; it will be a working initial appendix to a future All-Russia Construction Code on the tsunami protection of coastal cities. Such a map for the Black Sea is prepared as a first draft. A tsunami hazard map for the Caspian Sea is under consideration.

It is very important to estimate the tsunami risk of existing coastal cities, design new marine structures, and direct the creation of tsunami protected human settlements. By researching the interaction of long waves with coastal and on-water structures of various form and size, we will understand design models and loads.

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