

A METHOD FOR MATHEMATICAL MODELLING OF TSUNAMI RUNUP ON A SHORE

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Abstract. The paper is devoted to construction of numerical algorithms for modelling tsunami runup on beaches. Comparing numerical accounts both with analytical solutions, and with experimental data was executed.

Key words. Mathematical model, tsunami runup, shallow water, numerical algorithm, finite difference methods

1. INTRODUCTION

Recent progress in numerical modelling of tsunami is due to the increasing demand for protection of disaster prone objects. A new generation of national tsunami warning systems is based on the local networks tuned to capture the geographical, morphological and social factors peculiar to the protected coast. Local networks provide an alternative to the larger regional systems developed before. They allow for better response times and higher precision predictions, and not only reduce the overall damage from natural hazards and assure protection of potentially dangerous objects as nuclear power plants situated in the coastal zone or nuclear power driven vessels, but also decrease the probability of a false alert.

With the development of such systems new efficient methods for modelling of tsunami waves transformation in the coastal zone and runup on the shore are required.

The generally accepted mathematical model of runup is the system of equations describing the propagation of a long wave over a flat bottom towards the coast with a constant slope. Different versions of long wave equations such as the Boussinesq equation or non-dispersive shallow water equations had been proposed. Studies in one-dimensional modelling of wave runup on a slopping beach distinguish three ranges of the slope angle, α . These ranges correspond to gentle ($\tan \alpha \ll 1$) moderate ($\tan \alpha \sim 1$) and steep ($\tan \alpha \gg 1$) slopes.

The case of a *gentle* slope secures the choice of nonlinear shallow water theory equations for long waves, as the vertical projections of the acceleration of fluid

particles are relatively small. Most waves were observed to break approaching the shore. In the framework of nonlinear model the characteristic nonlinearity distance is introduced. If the nonlinearity distance is close to the length of the slope, then hyperbolic nonlinear equations of shallow water theory in the form of conservation laws can be applied.

Waves interacting with a *moderate* slope typically reflect from the shore without breaking. Nonlinear shallow water equations are widely used for the runup problem, but a detailed description of the fluid motion near the point of splash requires a proper account of the vertical acceleration of the particles. Nevertheless the nonlinear model provides for an accurate estimation of the maximal value of the inundation.

The shallow water model is not applicable for *steep* slopes, as the vertical acceleration of the particles is significant. Good approximation can be achieved by substituting the shore slope by an impenetrable vertical wall with the corresponding modification of the boundary conditions. Again the maximal runup height can be estimated from the equations of shallow water theory.

The main contribution of the work is the description of a numerical model for tsunami wave propagation and runup in a bay with irregular topography of the bottom. The solution is difficult to estimate *a priori* because of the strong effect of the bottom shape on the wave transformations near the shore. Description of wave propagation over a bottom of complex shape and an estimation of the runup height is based on the shallow water theory equations. A finite-difference method of *straight-through calculation*, which captures discontinuities of the solution, had been developed for a fixed grid over a rectangular domain. The computational domain represents the water bay with the adjacent shore. The scheme allows for the computation of the shoreline at every moment $t = n\Delta t$.

2. ONE-DIMENSIONAL NUMERICAL ALGORITHMS

The mathematical model is based on nonlinear non-dispersive equations. Let

$$\mathbf{W} = \begin{pmatrix} H \\ Hu \\ Hv \end{pmatrix}, \mathbf{F} = \begin{pmatrix} Hu \\ Hu^2 + H^2/2 \\ Huv \end{pmatrix}, \mathbf{G} = \begin{pmatrix} Hv \\ Huv \\ Hv^2 + H^2/2 \end{pmatrix}, \mathbf{Q} = \begin{pmatrix} 0 \\ gHh_x \\ gHh_y \end{pmatrix}.$$

The matrix form of the equations over the components $u = u(x, y, t)$ and $v = v(x, y, t)$ of the depth average velocity is:

$$\mathbf{W}_t + \mathbf{F}_x + \mathbf{G}_y = \mathbf{Q}. \quad (1)$$

Here $h = h(x, y)$ is the depth measured from the still water level; $H(x, y, t) = h(x, y) + \eta(x, y, t)$ is the total water depth varying in time; and $\eta = \eta(x, y, t)$ is the free surface elevation; and g is the gravitational acceleration.

Consider one-dimensional shallow water equations in a domain with a moving boundary. A number of finite-difference schemes were compared in order to choose a suitable numerical method for the tsunami runup problem [3].

Among the schemes frequently used to approximate nonlinear shallow water equations are the MacCormack scheme, the Aracawa scheme, the Ousher scheme

and the Lax scheme. The former two have the second order of approximation in space and time, while the latter are of the first order.

The choice of a scheme had been based on the comparison of the numerical solution with the exact solution or a solution obtained by more accurate models, such as nonlinear dispersive models. One of the exact solutions of this kind is represented by a solitary wave

$$\eta(x,t) = \eta_0 \operatorname{sech}^2 \left\{ \left(\frac{3\eta_0}{4h_0^2(h_0 + \eta_0)} \right)^{\frac{1}{2}} (x - x_0 - ct) \right\}, \quad u = \frac{c\eta_0}{h_0 + \eta_0}, \quad (2)$$

where $c = \sqrt{g(h_0 + \eta_0)}$. Experimental study of the convergence properties of the four schemes mentioned above was carried out on solutions (2), which is an analytical solution of the more accurate long-wave model (see [3]). A basin was specified by a constant depth $h_0 = 1$ and had a length five times the length of the wave. A sequence of uniform grids with increasing resolution was considered. The MacCormack scheme was shown to achieve good accuracy on a coarser grid [3].

We proceed with the description of the implemented algorithms. When the computational domain is fixed and coincides with the original domain an algorithm consists of a finite-difference scheme and a correction procedure on the nodes close to the shoreline.

Five algorithms were studied in the one-dimensional case.

Algorithm 1. A finite-difference scheme in a fixed line segment represents the simplest method for runup modelling. The numerical domain includes "underwater" and "dry" points. The method is defined by the grid resolution, time step and the minimal depth, h_0 , such that a layer of water of depth less than h_0 is considered dry. The total depth and velocity over the dry regions are set to zero. Calculations in the entire domain including water and the shore were performed using several schemes as the MacCormack scheme on a non-staggered fixed grid and the second-order scheme with central differences on a staggered fixed grid. The value of h_0 can be chosen by gradually decreasing this parameter in a series of computations until the shoreline becomes stable. In practice this value corresponds to the characteristic size of the irregularities of the bottom. For a monotone scheme and a gentle bottom slope it can be set to zero.

Algorithm 2. It is possible to consider another algorithm based on the MacCormack scheme in a fixed domain. In this method dry regions of the bottom are represented as covered by a thin layer of water of constant depth [3].

Algorithm 3. Computations in the points of the mesh near the shoreline depend on the direction of its movement. In the course of modelling of the runup stage new points are involved into the computation. In the run-down stage the exclusion condition is checked for each point of the shoreline. A special procedure is used to specify the initial values at the points freshly included.

Algorithm 4. When the oscillations of the coastal line are small the points on the shoreline marked as dry can be checked on the next time step according to the following procedure. Initial approximation of the total depth H is extrapolated on each step from inside the domain of fluid, and then corrected to satisfy the continuity equation.

Algorithm 5. Computations in a domain with a moving boundary require complicated program flow control. They can be avoided by mapping a variable size

domain into a fixed domain. Earlier a second-order scheme with the approximation of spatial derivatives by central differences had been used in the fixed domain. We have used the MacCormack scheme to approximate the equations after the transformation.

Algorithms providing for more accurate tracking of the shoreline are known, but they are considerably more difficult in implementation and in computational complexity, especially in the two-dimensional case.

Five algorithms described above were compared in the one-dimensional case on a set of problems of modelling a wave specified by a continuous initial elevation (solitary and harmonic wave) or with a single discontinuity (a bore). The physical domain represented a part of a basin with a constant depth area merged with a flat rising slope. The results were published in [3].

Another test set was based on a problem with known exact solution [2]. Let's consider initial perturbation defined by the following equation:

$$\eta = \varepsilon \left[1 - \frac{5a^3}{2(a^2 + \sigma^2)^{3/2}} + \frac{3a^5}{2(a^2 + \sigma^2)^{5/2}} \right], \quad x = -\frac{\sigma^2}{16} + \varepsilon \left[1 - \frac{5a^3}{2(a^2 + \sigma^2)^{3/2}} + \frac{3a^5}{2(a^2 + \sigma^2)^{5/2}} \right].$$

The results are shown on Figure 1. Here 500 grid nodes were used. The analytical and numerical solutions differ only near the boundary at the final time (dash lines). Table contains the runup values obtained by the methods listed above.

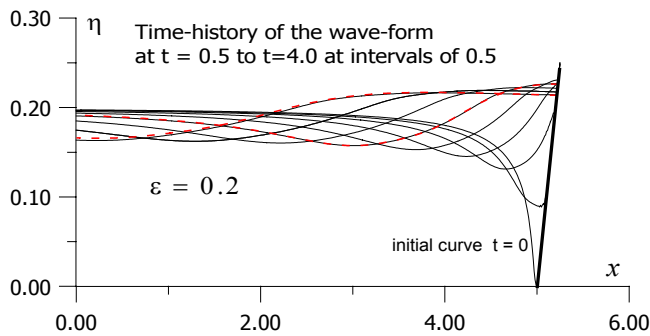


Figure 1. A comparison of analytical and numerical solutions.

Table. A comparison of runup values calculated by the methods

	Method of calculation	Runup value R
1	Analytical solution	R=0.2314
2	MacCormack scheme (moving grid tracking shoreline)	R=0.2321
3	Staggered explicit "box" scheme (moving grid)	R=0.2360
4	MacCormack scheme (author's variant, stationary grid)	R=0.2350
5	The same but with smoothing procedure of the second order of accuracy	R=0.2250
6	The same but smoothing procedure is of the first order	R<0.1750

The proposed algorithm was observed to be efficient regarding the utilisation of the computational resources, and to produce the values of maximal runup height in good agreement with the results obtained by more complicated methods. This algorithm was generalised for two-dimensional problems, and in the next sections

we describe the generalised algorithm. Note that not all the other methods can be modified for the two-dimensional case.

2. NUMERICAL ALGORITHM FOR A BASIN WITH A COMPLEX SHAPE

Finite-difference methods are frequently applied for two-dimensional problems of the long wave runup. Some of them use moving curvilinear grids while other carry computations on stationary rectangular grids. Each approach has its advantages and drawbacks. In the paper a finite-difference method on a rectangular grid in a fixed domain is considered. Having the advantage of simpler logical structure it can be used to handle arbitrary bottom topography and curvilinear coastal line. Being suitable for a wide variety of problems it loses in accuracy. The accuracy can be increased if the scheme has additional convergence properties. Theoretically an arbitrary accuracy level can be achieved at the expense of higher grid resolution.

The domain of a straight-through calculation method for tsunami wave runup problems usually contains both the water basin and the adjacent shore. The numerical domain is covered with a regular grid. The function reflecting the depth or elevation over the still water level is defined at each node. Construction of a numerical model requires special handling of the nodes corresponding to the shore. Several approaches to solve this problem had been proposed in the literature.

Method 1. Velocity and total depth are set to zero over the shore.

Method 2. A thin water layer kept from flowing down the slope by friction covers the shore.

Method 3. An artificial thin water layer of constant depth is maintained on the shore.

Despite the clear physical intuition behind and comprehensive coverage in the literature, the second method lacks mathematical justification. The third approach had been studied in one-dimensional case rather well. In the rest of the article the first method will mainly be considered. The advantage of this method is a clear physical interpretation and the mathematical motivation from the point of view of conservation laws.

Consider the system of conservation laws in the integral form, corresponding to the differential equation (1)

$$\oint_{\partial\omega_t} \mathbf{W} dx dy + \mathbf{F} dt dy + \mathbf{G} dt dx + \int_{\omega_t} \mathbf{Q} dt dx dy = 0 \quad (3)$$

in a rectangular domain Ω on the Oxy plane, which corresponds to an image of the basin with the adjacent shore under orthogonal projection on the horizontal plane. The domain Ω does not change in time and the process is restricted to the volume $Q_t = \Omega \times [0, t]$, however a part of Ω covered by water is variable and is divided from the shore by the moving shoreline.

The total water depth $H = h + \eta$ can be used to distinguish between the water area and the shore. The function $H = H(x, y, t)$ is nonnegative and the equation $H(x, y, t) = 0$ defines the moving shoreline. The function can be extended over the whole domain Ω by setting it to zero on the shore. The same symbol will be used to denote a function thus extended. The decomposition of the domain into the water

area $\Omega_t^{(1)} = \{(x, y) : H(x, y, t) > 0\}$ and the shore area $\Omega_t^{(2)} = \{(x, y) : H(x, y, t) = 0\}$ can be expressed as $\Omega = \Omega_t^{(1)} \cup \Omega_t^{(2)}$. Velocity components u and v can also be set to zero on the shore. Finally define a nonpositive function $\tilde{h}(x, y)$ in the region $\Omega_t^{(2)}$ as the height of the surface over the still water level taken with the opposite sign. This function can be considered as a continuation of the still water depth function so $h(x, y)$ can also be considered defined in the entire domain. We assume the curves $h(x, y) = 0$ and $\tilde{h}(x, y) = 0$ to coincide.

Now all the functions appearing in the integral expression of (3) are defined in the entire domain Ω . The equation holds in the cylinder Q_t ; it trivially holds in $\Omega_t^{(2)}$ as the expression under the integral sign is zero.

Thus the problem stated in a variable domain $\Omega_t^{(1)}$ is reduced to a rectangular domain Ω . Numerical solution can be obtained by a finite-difference method over the entire numerical domain, so that the shoreline will be computed automatically.

To construct the numerical algorithm we approximate the integral (3) in the domain $\Omega_0 \times [n\Delta t, (n+1)\Delta t]$ over the unit rectangle Ω_0 with sides $2 \times \Delta x$ and $2 \times \Delta y$ by means of the finite-difference scheme of the MacCormack type:

$$\begin{aligned} & (\tilde{\mathbf{W}}_{mk}^{n+1} - \mathbf{W}_{mk}^n) \Delta x \Delta y + (\mathbf{F}_{mk}^n - \mathbf{F}_{m-1k}^n) \Delta t \Delta y + (\mathbf{G}_{mk}^n - \mathbf{G}_{mk-1}^n) \Delta t \Delta x = \mathbf{Q}_{mk}^n \Delta t \Delta x \Delta y, \\ & \left(\mathbf{W}_{mk}^{n+1} - \frac{1}{2} (\tilde{\mathbf{W}}_{mk}^{n+1} + \mathbf{W}_{mk}^n) \right) \Delta x \Delta y + \frac{1}{2} \left((\tilde{\mathbf{F}}_{m+1k}^{n+1} - \tilde{\mathbf{F}}_{mk}^{n+1}) \Delta t \Delta y + (\tilde{\mathbf{G}}_{mk+1}^{n+1} - \tilde{\mathbf{G}}_{mk}^{n+1}) \Delta t \Delta x \right) \\ & \quad - \frac{1}{2} \tilde{\mathbf{Q}}_{mk}^{n+1} \Delta t \Delta x \Delta y = 0, \end{aligned} \quad (4)$$

$$\mathbf{Q}_{mk}^n = \begin{pmatrix} 0 \\ g \frac{H_{mk}^n + H_{m-1k}^n}{2} \cdot \frac{h_{mk} - h_{m-1k}}{\Delta x} \\ g \frac{H_{mk}^n + H_{mk-1}^n}{2} \cdot \frac{h_{mk} - h_{mk-1}}{\Delta y} \end{pmatrix}, \quad \tilde{\mathbf{Q}}_{mk}^{n+1} = \begin{pmatrix} 0 \\ g \frac{\tilde{H}_{m+1k}^{n+1} + \tilde{H}_{mk}^{n+1}}{2} \cdot \frac{h_{m+1k} - h_{mk}}{\Delta x} \\ g \frac{\tilde{H}_{mk+1}^{n+1} + \tilde{H}_{mk}^{n+1}}{2} \cdot \frac{h_{m+1k} - h_{mk}}{\Delta y} \end{pmatrix},$$

$\tilde{\mathbf{F}}_{mk}^{n+1} = \mathbf{F}(\tilde{\mathbf{W}}_{mk}^{n+1})$, $\tilde{\mathbf{G}}_{mk}^{n+1} = \mathbf{G}(\tilde{\mathbf{W}}_{mk}^{n+1})$. Here $\Delta t, \Delta x, \Delta y$ are the grid steps. As the values H_{mk}^n , $(Hu)_{mk}^n$, $(Hv)_{mk}^n$ are determined using the difference scheme (4) above, velocities calculated at small values of H tend to be inaccurate. We pick a relatively small value H_{min} of the same order of magnitude as the irregularities of the bottom. The regularization procedure is applied so that a node (m, k) with $H_{mk}^n < H_{min}$ is considered dry, so that the constraints $H_{mk}^n = 0$, $u_{mk}^n = 0$, $v_{mk}^n = 0$ hold. The error arising from this correction is estimated by comparing the results of computations for a decreasing sequence of H_{min} : $H_{min} = 10^{-3}, 10^{-4} \dots$ (in the dimensionless formulation).

The algorithm consists of the following steps:

1. In all internal nodes of the grid over the domain Ω , the values of H_{mk}^n , $(Hu)_{mk}^n$, $(Hv)_{mk}^n$ are calculated by the finite-difference scheme.

2. The condition $H_{mk}^{n+1} > H_{\min}$ is being checked in each node; and if satisfied, the velocities are updated $u_{mk}^{n+1} = (Hu)_{mk}^{n+1} / H_{mk}^{n+1}$, $v_{mk}^{n+1} = (Hv)_{mk}^{n+1} / H_{mk}^{n+1}$, otherwise $H_{mk}^{n+1} = 0$, $u_{mk}^{n+1} = 0$, $v_{mk}^{n+1} = 0$.

3. The shoreline is determined as the boundary of the set of all nodes with $H_{mk}^{n+1} > 0$.

The algorithm is easy to implement. There are questions on both the accuracy of this method in general (with respect to the convergence to the solution of the approximated differential problem) and on the precision of the estimation of particular values, such as the values of maximal runup and average velocity of water approaching the shoreline. A number of test problems was considered for a solitary wave approaching the shore. The convergence of the algorithm was studied by considering a refining sequence of grids.

In order to determine the value of the maximal runup the highest position of the wave front on the beach should be obtained. In the current notation it is equivalent to computation of the boundary of a domain of all points which were covered by water at a moment $t > 0$, so that the full depth H was strictly positive.

Numerical experiments and theoretical analysis of the difference scheme show that when the grid refinement is applied the algorithm attains good estimation of the maximal runup for the whole range of shore slopes. However in practical computations the necessary number of points over the length of the slope is not always available if the slope is steep. A special extrapolation procedure had been developed to correct a position of a shoreline where the bottom surface has sharp gradients. The proposed technique is easy to implement and the question of its applicability should be decided depending on the required accuracy.

3. TESTING THE NUMERICAL ALGORITHM

One of the most typical tasks of wave hydrodynamics is the problem of simulating a wave regime, which results from the interaction of an incoming wave with an island. This is to describe the transformation of the wave in the coastal zone, compute the maximal runup. To test the program against intended to solve such tasks, it is necessary to find a rather complete set of experimental data together with the detailed description of test basin, the initial data, and the results of observations.

Proceedings of International workshop on runup models (Yeh *et al.* [5]) are an established source of empirical information for wave hydrodynamics. The book contains the four test problems that were presented to the scientific community for comparing and verification of mathematical models of long ocean waves. The first demonstration of the algorithm and its implementation we describe, is the solution of a test problem of a solitary wave running up a conical island (Briggs *et al.* [1]).

PROBLEM 1

The wave tank of the Waterways Experiment Station of the U.S. Army Corps of Engineers is a rectangular basin with a flat bottom of width $L_y = 30$ m and of length $L_x = 25$ m with a conical island in the center.

Let the Oy axis be parallel to the surface of the wave generator, and let the Ox axis be directed to the island at the still water level. The origin of the coordinate system coincides with the edge of the wave generator (Figure 2). The center of the island is located at the point $x_0 = 13$ m, $y_0 = 15$ m. We will consider a planar solitary wave with the amplitude to the water depth ratio being equal to 0.1.

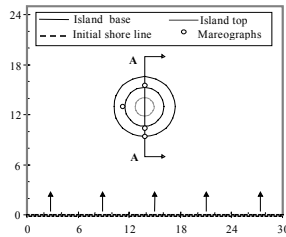


Figure 2. Scheme of water area: island contours and gages location (top view)

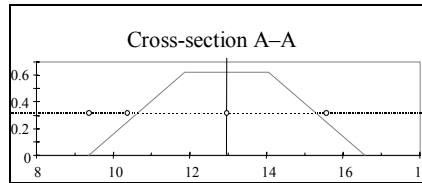


Figure 3. Scheme of island contours, shore line and gages locations (side view)

The experimental data and the results of our computations are presented as water level charts recorded by gages at four points inside the basin (Figure 3). The first gage was set in front of the island ($x_1=9.4$, $y_1=15.0$, local depth $D_1=0.32$ m). The second gage was set near the still water line on the island ($x_2=10.4$, $y_2=15.0$, $D_2=0.082$ m). The third point was on the left side of the island ($x_3=13.0$, $y_3=12.42$, $D_3=0.079$ m). The last chart is from a gage on the rear side of the island ($x_4=15.6$, $y_4=15.0$, $D_4=0.083$ m). The maximal runup height along the island was also recorded.

The external boundaries of the computational domain are the rectangle sides of the basin. On one of the sides a non-stationary boundary condition is specified to simulate the incoming wave. Three other boundaries are simulated as "transparent boundaries", transmitting the solution outwards without reflection. The purpose of the numerical experiment is to describe the evolution of the shoreline and to estimate the maximal runup height over the island boundary and at the rear side of the island in particular.

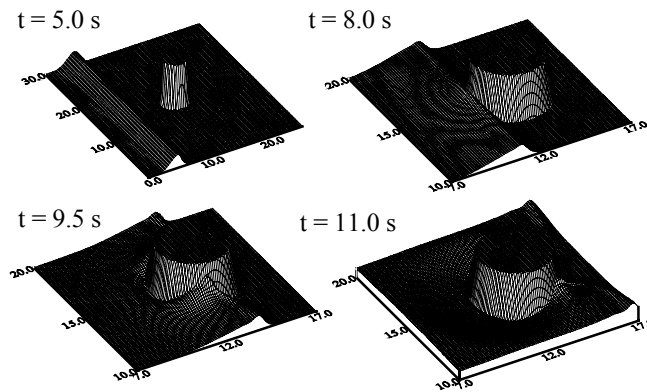


Figure 4. Solitary wave runup on a conical island. Wave profiles at different time.

Figure 4 presents the plane solitary wave propagates over a flat bottom and the process of an interaction with the island. From $t=1.2s$ to $t=5s$ the wave had passed a distance equal to an effective wavelength. The front becoming steeper is characteristic to the equations of hyperbolic type.

Results of the numerical solution are shown on the figures below. The most typical features of the wave evolution in the process of its interaction with the island can be seen. Figure 4 presents the snapshots of free-surface profiles at different moments of time. The solitary wave passes along the model island with an increase in amplitude in the nearest vicinity, and forms a system of circular waves behind. The circular waves then leave the domain through the transparent border.

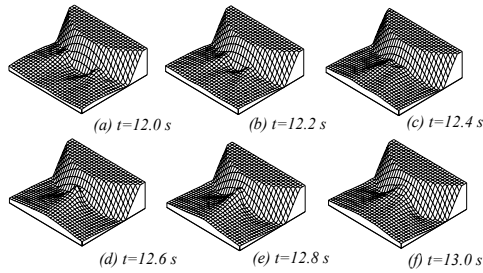


Figure 5. The wave patterns at the lee side of the island.

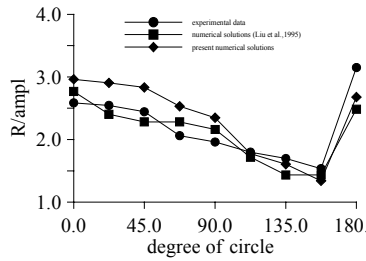


Figure 6. The runup heights around the island.

The wave pattern at the lee part of the island is of particular interest. Figure 5 shows the waves passing the island to interact and to form a splash with the runup height exceeding the one at the front. Numerical estimation of the runup height behind the island is less than the experimental values, which could be explained by the effects of artificial dissipation introduced on the numerical stage (see Figure 6).

Comparison of the time charts (see Figure 7) shows the numerical solution to capture both the qualitative and quantitative features of the experimental data with acceptable accuracy. The transparent boundary conditions on the sides of a basin work almost perfectly without introducing any significant disturbance in the wave picture, while the absorbing boundaries of the experimental basin show a noticeable reflection.

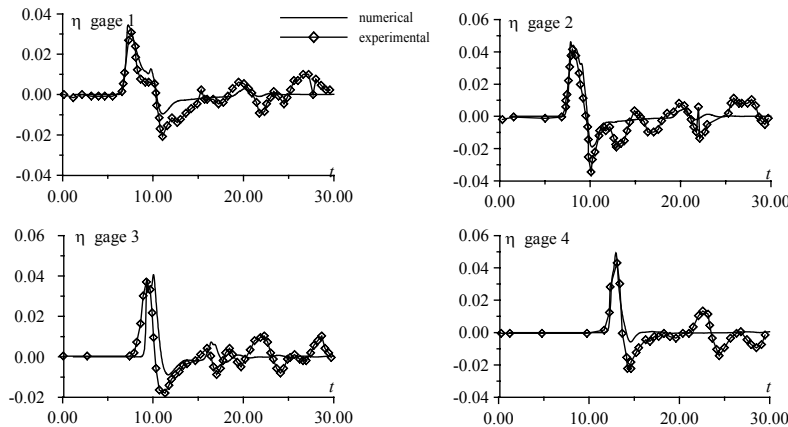
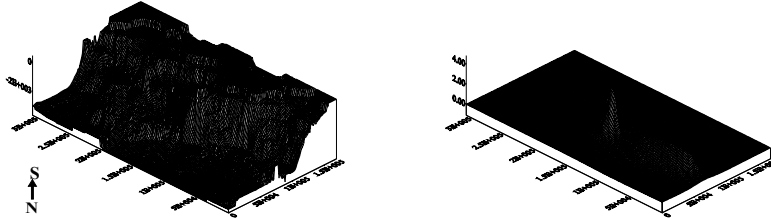


Figure 7. Water levels at the fixed points (see Figure 2).

PROBLEM 2

The second test problem is based on the real tsunami, which had occurred on July 12, 1993 in Japan. The problem had been chosen due to the availability of the detailed data on the bottom and shore relief, and on the shape of the initial elevation of the free surface. The data was obtained from the Hokusai database maintained by the Disaster Control Research Centre of Japan [4]. Figures 8 present the schematic view of the relief of the bottom and the initial form of the wave.



Figures 8. The bottom relief and the initial surface distribution.

The tsunami occurred near Hokkaido after a strong Nansei-oki earthquake with the magnitude of approximately 7.8 on July 12 at 22:17 NTP. At about 22:22, after the observatory in Sapporo had issued a tsunami warning message, the first wave approached the shore of the Okushiri Island. In five minutes the wave had reached the cities of Setana and Taisei on the eastern coast of Hokkaido.

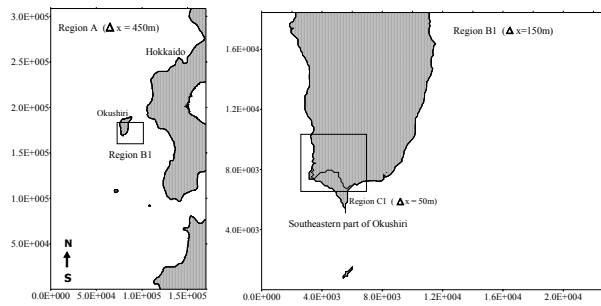


Figure 9. Schematic representation of the water area.

A sequence of three computational grids was used. A rough grid covered the entire domain (region A on the Figure 9) of the size 168.75×307.8 km with a step corresponding to a distance of 450m. The grid was stored in an array of 379×687 points. Two other grids were constructed to capture the details of the interaction of the wave with the island. They cover the regions B1 and C1 on the Figure 9 with the steps corresponding to 150m and 50m distances respectively.

The Figure 10 presents the process of the wave propagation in the entire domain as computed over the coarse grid. On this level of detail the smaller islands around Okushiri can be safely treated as conical.

On the Figure 11 the picture of flooding of the "tip" of the Cape Aonae (the southern coast of Okushiri) is shown. A high splash can be seen in the neighborhood of Hamatsumae located on the lee side of the island. Such degree of detail could only be obtained with the use of a grid with the smallest step of 50m.

The runup height distribution over the entire coast of the Okushiri Island as shown on the Figure 12, had been computed over the coarse grid (the domain A). The runup values on the coasts of Aonae and in the region of Hamatsumae obtained

from the computations on the finest grid are shown on the Figure 13. The flood zone is depicted on the same picture.

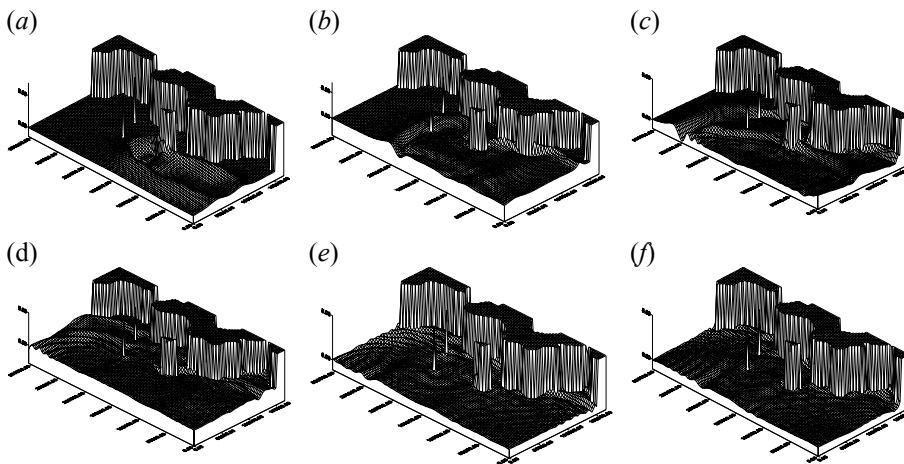


Figure 10. Wave pictures in the domain A at different moments of time.

Again the comparison of numerical results with the experimental data from the Hokusai database shows good correspondence between the two.

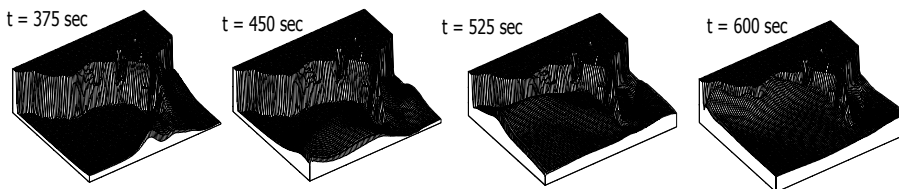


Figure 11. Flooding of the Cape Aonae (the region C1). The last image shows the flooding of Hamatsumae district.

Comparing results of numerical calculations with data obtained on learning of "tracks" of real manifestation of a tsunami and of observations of the eyewitnesses (see [4]), we see rather good correlation of values of maximum runup. It is necessary to remark however, that the correct application of used here computing algorithms needs a finer grid.

In conclusion we remark, that the algorithm has good potential for application to the problem of tsunami. The effect on the coastal structures can be predicted with good accuracy from estimated values of the runup height. The implementation can be extended incorporating linear dispersive and nonlinear dispersive models in addition to the nonlinear model used so far. Combining them in a single framework provides for the most accurate simulation of the natural phenomena.

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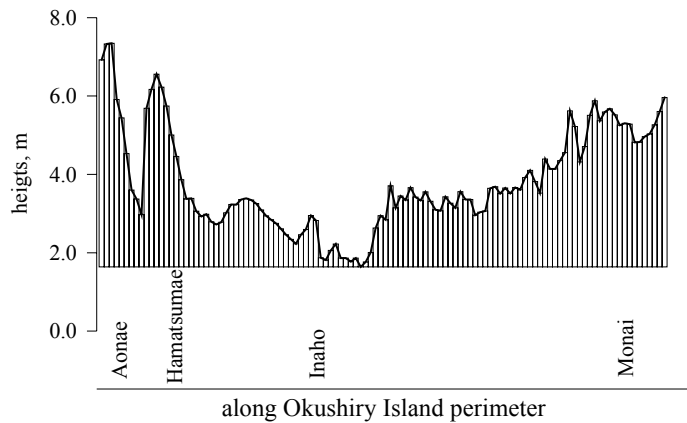


Figure 12. Maximum runup heights along the shore of Okushiri

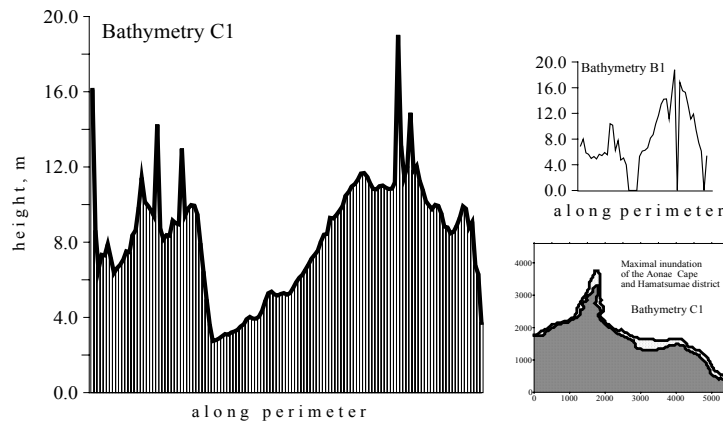


Figure 13. Maximum runup heights along the Aonae Cape.

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