Hybrid Tsunami Modeling Infrastructure: Tsunami Source Data and Bathymetry Editor

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ABSTRACT
The important part of the tsunami science is focused on studying the considerable influence of natural geographical objects, like islands and coast bathymetry, on the tsunami waves. Currently, such investigations are mostly implementing by physical modeling allowing obtaining good results on impacting submarine barriers on tsunami wave propagation but actually very expensive. We are designing a system allowing numerical computer simulations for crucial coastal areas supporting so-called hybrid bathymetry that combines natural and artificial underwater objects as well as tools allowing the user to manipulate with them. The paper describes the main features the original Bathymetry and Tsunami Source Data Editor that allows tuning/editing bathymetric and tsunami source data by including/removing artificial barriers as well as specifying their placement, shapes and sizes.

Categories and Subject Descriptors
I.6.7 [**Simulation and Modeling**]: Simulation Support Systems – *Environments, Animation, Visual.*

General Terms
Algorithms, Design, Experimentation.

Keywords
Tsunami Modeling, Integration of Heterogeneous Software Components, Hybrid Bathymetry, Tsunami Source and Bathymetry Data Editor

1. INTRODUCTION
The important part of the tsunami science is focused on studying the considerable influence of natural geographical objects, like islands and coast bathymetry, on the tsunami waves. While the complete damage assessment for the Great Japanese Earthquake event is still underway, the immense impact of this tsunami raises questions about mitigating the impact for such an event at different time scales, from real–time tsunami warning guidance to long–term hazard assessment. Assessing the use of real–time tsunami forecasting tools is an important part of this process. The necessity to embed modeling tools is shown for Earthquake and Tsunami Warning System for Natural Disaster Prevention and Defence Systems [1-2]. One such example known as "Matsushima effect" showed big influence of placement and sizes of natural geographical objects like islands and bathymetry on the tsunami wave parameters such as wave height and speed.

Currently, such investigations are mostly implementing by physical modeling in basins (several meters in length and less than one meter in depth) [3]. It was also shown that parameters of simulations could be transformed to natural conditions. These experiments showed good results on impacting submarine barriers on tsunami wave propagation but actually very expensive.

In addition to the physical modeling, we are designing a system allowing numerical computer simulations for crucial coastal areas supporting so-called hybrid bathymetry combining natural and artificial underwater objects as well as tools allowing the user manipulate with them [4-5] in order to make it more intensive. Accordingly, The aim of modeling process is in finding preliminary suitable number, sizes, and placement of submarine bathymetry objects in order to minimize the dangerous tsunami wave parameters (height and speed). In this way it may be possible to design and build a set of digital artificial objects (islands) that can be used to protect the coastal areas. In particular, such protection could be of extreme value in highly populated areas, as well as in industrial areas (e.g. nuclear plants, factories, airports, etc.).

The paper describes the main features the original Bathymetry and Tsunami Source Data Editor (TSB-editor) that allows tuning/editing bathymetric and tsunami source data by including/removing artificial barriers as well as specifying their placement, shapes and sizes. The rest of the paper is organized as follows. Section 2 explains the mathematical model for simulating wave propagation explaining data source sets needed for numerical modeling. In Sections 3, we show main features of the TSB-editor architecture and interface. Section 4 describes present results of tsunami modeling with hybrid bathymetry designed via the TSB-editor. Finally, we conclude with remarks and comments about future work.

2. TSUNAMI MODELING FEATURES

2.1 Theoretical Background

There are a number of algorithms and models developed for the tsunami risk mitigation covering phases of generation, propagation from the deep ocean to the coastal areas. The most known, accurate and widely used are TUNAMI [6] and MOST [7-8] packages calculating the long wave propagation in the ocean by the so-called shallow-water differential equations:

$$\begin{cases} H_t + (uH)_x + (vH)_y = 0, \\ u_t + uu_x + vu_y + gH_x = gD_x, \\ v_t + uv_x + vv_y + gH_y = gD_y, \end{cases} \tag{1}$$

where $H(x, y, t) = h(x, y, t) + D(x, y, t)$, h is the water surface displacement, D is depth, u(x, y, t) and v(x, y, t) are velocity components along the axis' x and y'. g is acceleration of gravity. Accordingly, the tsunami propagation velocity does not depend on its length and is expressed by the so-called Lagrange formula $c = \sqrt{g(D+\eta)}$ [5,6] that plays the key role for the long-wave (tsunami) kinematics. The horizontal flow velocity depends on the wave amplitude and water depth

$$u = \eta\sqrt{\frac{g}{D}} \ . \tag{2}$$

The numerical algorithm is based on splitting the difference scheme, which approximates equations (1) by spatial directions as well as permits to set boundary conditions for a finite difference boundary value problem using a characteristic line method. The splitting method used for shallow wave equations (2) comprises a consecutive numerical solution of two one-dimensional systems of equations:

$$\begin{cases} V_t + UV_x = 0 \\ U_t + UU_x + gH_x = gD_x \\ H_t + (UH)_x = 0 \end{cases} \qquad \begin{cases} V_t + VV_x + gH_x = gD_x \\ U_t + VU_x = 0 \\ H_t + (VH)_x = 0 \end{cases} \tag{3}$$

Eigenvalues of (3) are real and different, and the system can be

$$\begin{aligned} &V'_t + \lambda_1 V'_x = 0, \\ &P_t + \lambda_2 P_x = 0, \\ &Q_t + \lambda_3 Q_x = 0, \end{aligned} \tag{4}$$

where $\lambda_1 = U$, $\lambda_{2,3} = U \pm \sqrt{gH}$ are eigenvalues, $V = V'$, $P = U + 2\sqrt{gH}$, $Q = U - 2\sqrt{gH}$ are the Riemann invariants. The characteristic line method has been used to set the boundary conditions for the system. For the numerical solution of the system, the following finite difference scheme is used:

$$\frac{\vec{W}_i^{n+1} - \vec{W}_i^n}{\Delta t} + A\frac{\vec{W}_{i+1}^n - \vec{W}_{i-1}^n}{2\Delta x} - A\Delta t\frac{A(\vec{W}_{i+1}^n - \vec{W}_i^n) - A(\vec{W}_i^n - \vec{W}_{i-1}^n)}{2\Delta x^2} =$$

$$= \frac{\vec{F}_{i+1} - \vec{F}_{i-1}}{2\Delta x} - A\Delta t\frac{\vec{F}_{i+1} - 2\vec{F}_i + \vec{F}_{i-1}}{2\Delta x^2}, \tag{5}$$

where

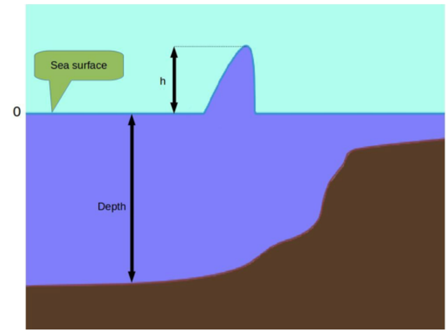
$$A = \begin{Bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{Bmatrix}, \vec{W} = (V', P, Q), \ \vec{F} = (0, gD_x, gD_x).$$

The criterion of stability is $\Delta t \le \Delta x / \sqrt{gH}$ requiring assignment of a smaller time step if a computational domain contains deep-water areas. Obviously, the digital bathymetry D and initial water elevation (tsunami source) are the key elements influencing to tsunami waves. In our experiments we use the MOST package [7-8].

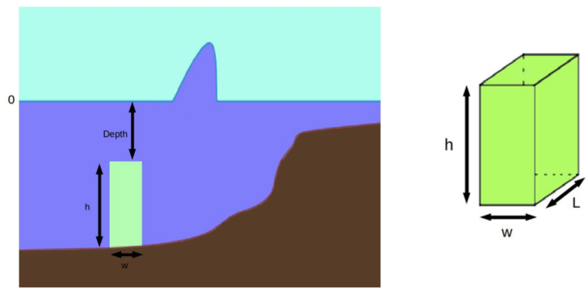
2.2 Bathymetry Data

Bathymetry is the measurement of the depth of water in oceans, rivers, or lakes [9-10]. Bathymetric maps look a lot like topographic maps, which use lines to show the shape and elevation of land features. On topographic maps, the lines connect points of equal elevation. On bathymetric maps, they connect points of equal depth. It can also indicate a seamount, or underwater mountain.

Figure 1 represents a way of coding the digitalized bathymetry and tsunami waves data. Depth values may be either negative or positive, but should all be understood to be negative. Elevations or wave heights are above sea level and considering to be positive. The gridded bathymetry is the two dimensional array that is used as a source data for modeling program. Additionally, it contains some information specifying longitude and latitude in order to associate these data with real geographic areas. Figure 1b shows a hybrid bathymetry obtained by recalculating the natural bathymetry and containing an artificial object. Shape, size and placement of this object are saved in a special file.



a)



b)

Figure 1. Natural and hybrid bathymetry

2.3 Tsunami Source Model

There is an initial water surface elevation as a result of numerical modeling of the elastic-plastic problem with seismic source with specified parameters. To study the ratio between the initial wave height and wave parameters near the coast, it is necessary to carry out a number of numerical experiments with specified initial parameters. Accordingly, the initial water surface displacement can be specified by ellipsoidal shape

$$H(i,j) = \left(1 + \cos(\pi \cdot \arg(i,j))\right) \cdot H_0$$

where H_0 is half of the water surface displacement at the central point (i_0, j_0) of the ellipse. The parameter *arg(i,j)* gives the ratio between the distance to the ellipse center and the distance to the ellipse border in this direction

$$\arg(i,j) = \left(\frac{(i-i_0)\cdot\cos(\beta) + (j-j_0)\cdot\sin(\beta)}{r_1} \right)^2 + \left(\frac{(j-j_0)\cdot\cos(\beta) - (i-i_0)\cdot\sin(\beta)}{r_2} \right)^2$$

Here r_1, r_2 are the ellipse axis length and β is the long axis azimuth. Figure 2 shows the shape of the two meters height ellipsoidal source with the axis' ratio equal to two, and the water height distribution along the ellipse axis.

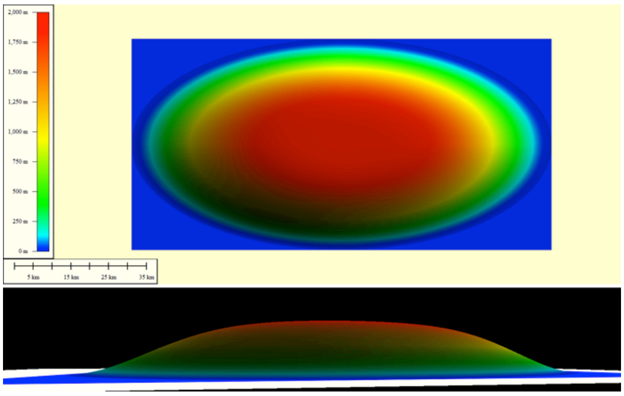


Figure 2. The shape and cross-section of a model ellipsoidal tsunami source

3. TSB-EDITOR ARCHITECTURE AND INTERFACE

TSB-editor was developed supporting object-oriented GUI-editing on bathymetric data as well as including/removing artificial objects with variable placement, shapes and size (Figure 3). As was pointed, above it manipulates with the gridded bathymetry as a two dimensional array that is used as a source data for modeling program. The editing process can be implemented using two windows named Controller and Viewer correspondingly (Figure 4). The Viewer window visualizes the state of the edit data, and Controller is used for specifying object parameters, control the editing mode, reading and saving bathymetry and tsunami source files, etc.

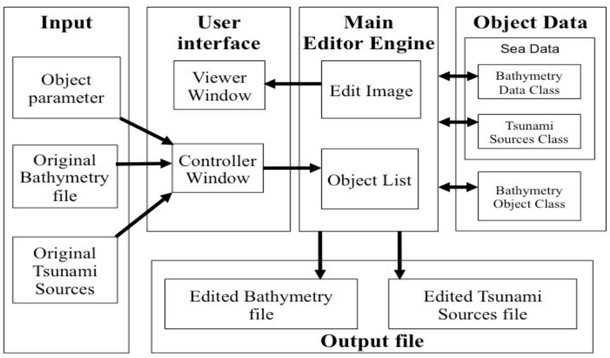


Figure 3. Main elements of the TSB-editor

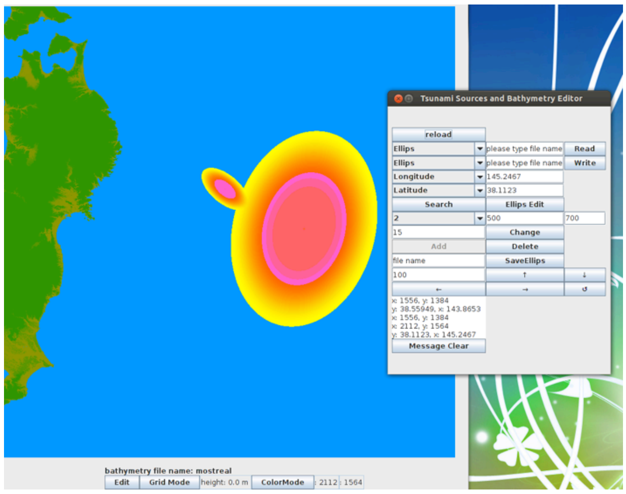


Figure 4. Interface of TSB-editor

An editing process is started from reading an bathymetry file and setup the editing parameters like array size, coordinates, etc. Then the user defines the object location by inputting directly its longitude and latitude values or getting position by clicking a picture on Viewer window. The user should specify height, width, angle and elevation/depth of an object that is generated by pressing the "ADD" button on the controller window. In any time the user can change any object by choosing it from a list, inputting new parameters, and fixing these changes by the "CHANGE" button. If the user would like to add a new object, user chose new object from list, a parameter is input and it's added.

The editor saves a file according to the edit mode (Tsunami sources or Bathymetry) including an edit history file. Every objects data is stored in a container of the vector type. The Object data has object number. This number is different respectively. The controller can search and edit every object data by object number. Objects data has object parameter and object's depth map (2-dimensional array data). Current version of the Editor is used the NOAA Bathymetry data. In future we are planning to extend it by other GIS data formats.

The editing is similar for both tsunami sources and bathymetry with a few differences. For bathymetry, the depth is expressed by a blue gradation, and an artificial object is also corresponding to this gradation. It should also be defined by its height and width. For tsunami sources, all sea surfaces have the same color, and the Tsunami waves height is expressed by a red colored gradation because of no relation to the sea depth. It requires specifying the side and lengthwise radiuses.

4. MODELING EXPERIMENTS

A set of numerical experiments was provided with hybrid bathymetry. Accordingly, the 2148x1074 knots gridded bathymetry was created for the Oppa Bay and the neighboring harbors (approximately 17 m). These data cover the geographical area from 141.41659º E to 141.75º E and from 38.5º N up to 38.6666º N. In Table 1, the results of ten numerical experiments are presented with the hybrid bathymetry of a parallelepiped shape barriers of different sizes and placement. Figure 5 shows a visual comparison of the

Tsunami wave behavior for natural (upper image) and hybrid bathymetry reflecting the case seven in the Table1.

Table 1. Source Data and Experimental Results

No	Object Place in °	Object Size, (km)	Object Climax, (m)	Max Wave (m)	Max Wave Place
0	None	None	None	3.10	None
1	38.577148 141.6129	9.443x 0.9443	-63	2.80	Dotted the coastline
2	38.577148 141.6129	4.721x 0.9443	-12	2.70	Dotted the coastline
3	38.577148 141.6129	9.443x 0.9443	-12	2.35	Intricate of South
4	38.577148 141.6129°	9.443x 0.9443	-63	2.80	Intricate of South
5	38.577148 141.5668	9.443x 0.9443	-35	2.75	Dotted the coastline
6	38.577148 141.566895	4.722x 0.9443	-35	2.75	Dotted the coastline
7	38.577148 141.566895	4.722x 0.9443	-7	2.50	Intricate of North
8	38.577148 141.566895	9.443x 0.9443	-7	2.40	Intricate of North

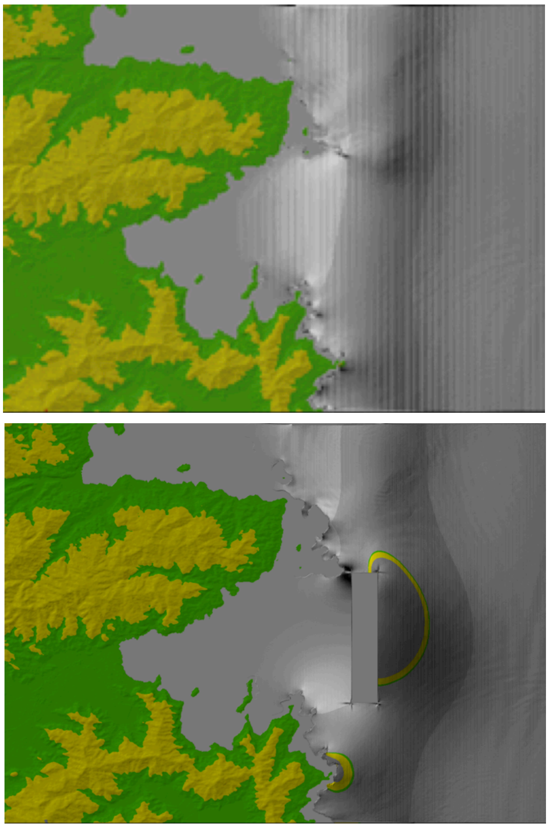


Figure 5. Visualization of Tsunami waves for natural (upper image) and Hybrid bathymetry of the Oppa bay

5. CONCLUSION

The current version of the Editor allows the user to manipulate with ellipsoidal shapes (for editing bathymetry and wave sources) described above as well as parallelepiped-like objects (for editing bathymetry) such as cubes, walls, etc. In the future we are planning to extend this set by pyramids, sphere, etc. The user can create composite objects using this set of elementary objects.

These results demonstrate a good possibility to realize this new type of tsunami modeling. As shown in figure, the tsunami wave behavior on hybrid bathymetry is significantly different from the natural one. This makes also possible to control the tsunami wave height by underwater artificial objects as well as provide studying features of the natural bathymetry.

6. ACKNOWLEDGMENTS

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