AN INTEGRATED PC-BASED RESEARCH AND INFORMATION SYSTEM FOR TSUNAMI RESPONSE AND MITIGATION

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ABSTRACT

As a result of a feasibility study, a concept for and a prototype of the Integrated PC-based Tsunami Research and Information System (ITRIS) was developed at the Tsunami Research Group of the Novosibirsk Computing Center, Russian Academy of Sciences. This concept is based on the integration of numerical models, observational and reference data, processing and analyzing tools, along with visualization and mapping software embedded inside the specially developed graphical shell providing the ability for fast and efficient manipulation of maps, models and data. The ultimate goal of the ITRIS Project is to develop an enhanced environment for IBM PCs and compatibles for the retrieval, visualization, and processing of data as well as for carrying out basic numerical experiments in the investigation of different aspects of the tsunami problem without the need for additional coding. The final product could be used not only as an interactive modeling system, but also as a convenient electronic textbook and reference book on tsunamis.

INTRODUCTION

A tsunami is a terrible disaster for a significant portion ofthe coasts of the Pacific and some other seas. In terms of the total damage and potential loss of lives tsunamis do not rank first among other natural hazards. Actually, they are fifth after earthquakes, floods, typhoons and volcanic eruptions. However, they have an extremely adverse impact on the socioeconomic infrastructures of a society. This is an impact which is strengthened by the suddenness of onset and widespread destruction of property and the high percentage of fatalities among populations exposed to a tsunami. The significance of this hazard has been increased in the last thirty years by the rapid growth of population and fast development of the coastal areas in many countries.

Numerical methods have been long and successfully used for mathematical modeling of tsunami generation, propagation and runup. The ability of numerical models to reproduce the basic features of this complicated natural phenomenon has been more than once demonstrated by the computer simulation of many historical tsunamis. However, up to now their application to the operative tsunami prognosis has been somewhat limited. This can be explained in three ways: first, the lack of time for issuing warnings in case of regional events; second, the lack of computational facilities in the existing tsunami warning centers; and, third, the lack of operational data on earthquake source parameters. At present, the first two reasons can be eliminated due to the development of new and effective numerical algorithms and, even to a greater extent, by a fast increase in the power of micro- and personal computers that are now available at the regional warning centers.

As a result of a feasibility study, the concept of the Integrated Tsunami Research and Information System (ITRIS) has been developed at the Tsunami Laboratory of the Novosibirsk Computing Center. This concept is based on the application of numerical models for the prediction of tsunami heights along the coast by implementation of a specially elaborated interactive computer technology that provides near real-time calculation of tsunami generation, propagation and run-up. This system also facilitates the interpretation of data and enhances the decision-making process through an intensive application of computer graphics, mapping and data analysis.

BASIC SYSTEM REQUIREMENTS

In elaborating the ITRIS we plan to meet the following basic requirements:

(1) it should be able to simulate all three basic stages of a tsunami - generation, propagation and run-up - and should be easily customized to any tsunamigenic regions of the Pacific and elsewhere;

(2) it should be applicable in the operational mode which means that numerical modes and algorithms should provide computational time less than the actual propagation time (typically 20-30 min);

(3) the system should have a modular structure allowing flexibility and adjustment to a particular application as well as be an open system providing the growth potential to keep abreast of research advancement;

(4) the system should have built-in comprehensive databases containing all the meaningful information related to the tsunami problem for the particular region;

(5) the system should have built-in computer mapping software providing the ability to display results and data on actual geographical bases;

(6) the system should have a friendly user interface based on a menu-driven approach.

The ultimate goal of the ITRIS Project is to develop an enhanced environment for IBM PCs and compatibles for retrieval, visualization and processing of data as well as for carrying out various numerical experiments in the investigation of different aspects of the tsunami problem without the need for further coding. The final product could be used not only as an interactive modeling system, but also as a convenient electronic textbook and reference book on tsunamis. The product may also be used as a computer-aided device for investigation of different aspects of tsunami problem including the long-term assessment of tsunami risk for particular region.

BASIC SYSTEM FUNCTIONS

The basic functions of the system are as follows:

(1) choice of an area for numerical experimentation within the Pacific region and automatic construction of the computational grids;

(2) computation of the initial displacement in the tsunami source on the basis of preliminary selected or operationally estimated earthquake source parameters;

(3) fast computation and plotting of the tsunami travel time charts with the generation of a list of travel times for the initially indicated points;

(4) computation of full dynamic tsunami wave field (displacement of water surface, components of particle velocity) at each "sea" grid point of the computational area;

(5) computation and plotting of tsunami wave forms at any indicated point of the computational grid;

(6) computation and plotting of the distribution of the maximum tsunami heights along the coast;

(7) computation and plotting of 3-dimensional pictures of the tsunami wave field at any given moment in time;

(8) retrieval and display of historical data on regional seismicity and tsunamis for any particular area of the Pacific.

FIELD OF APPLICATION

ITRIS is being developed for three basic application fields:

(1) in the regional tsunami warning centers in event-mode for the operational wave height prediction and the facilitation of decision-making process. This is to be achieved through intensive application of formalized expert knowledge in the field. The system is also designed for use at these sites in the pre-event mode for simulation and "playback" of possible warning situations, and for personnel training;

(2) in the governmental and non-governmental agencies responsible for tsunami mitigation efforts as inexpensive PC-based device for in-depth education and orientation of officials, public demonstrations and pre-event emergency planning;

(3) in research centers as an advanced computer-aided tool for carrying out numerical experiments for investigating different aspects of the tsunami problem.

MATHEMATICAL MODELS

As a model of the tsunami generation we use a dimensional dislocation model of an earthquake source placed within the homogeneous elastic halfspace. This conventional earthquake source model is described by six parameters: length of the fault plane L, width of the plane W, depth of the fault h, dip-angle d, strikeangle l and the amount of displacement D. The intensity of this source is represented by its seismic moment which is a product of rigidity of the medium, the area of the fault, and the amount of displacement over it. The vertical static displacement produced by the dislocational source is calculated by the algorithm described in (Gusiakov, 1978) and used as the initial condition for the tsunami propagation program.

If there are no operational data for the source mechanism, it is possible to input the tsunami source as a simple elliptical elevation with parameters (length, width and vertical elevation) defined by some correlation formula with the source magnitude.

The non-linear shallow water system is used for the modeling of tsunami propagation in a water layer with variable depth. This system is solved numerically by a specially elaborated algorithm based on the so-called splitting method and application of variable computation grids. An algorithm of this type diminishes computer time 5-6 fold in comparison with the conventional finite-difference methods and allows us to use a 32bit PC instead of a mainframe computer for near-real time tsunami calculation (Gusiakov, Marchuk, Titov, 1992).

The algorithm of the travel time computation is based on the calculation and comparison of travel times between the neighboring grid points over a 16-ray star (Marchuk, 1988). As compared to the conventional ray method for calculating travel times charts, this algorithm has a higher efficiency and stability in the regions of complicated bottom topography. On 66-Mhz 486 PC, it allows us to obtain a 1-hour travel time chart in several seconds of CPU time.

DATABASES

The built-in database is intended to be a comprehensive source of observational data on historical tsunamis in a particular region along with some additional reference information related to the tsunami problem.

At the moment the database consists of four basic parts:

1) EARTHQUAKES database contains the source data of regional earthquakes down to magnitude 4.0. Source information includes date, time, coordinates of epicenter, depth, magnitude (basically Ms), and seismic intensity followed by indexing to source data. All data can be cross-correlated and retrieved by geographical area, date, depth and magnitude.

2) TSUNAMIS database consists of four main parts: detailed source data of tsunamigenic events, coastal observation of wave heights, original description of tsunamis, and bibliographical references. Source data of tsunamigenic events are cross referenced to the earthquake database but contain the extended set of magnitudes including moment-magnitude Mw, tsunami-magnitude Mt, seismic moment, moment-tensor and source mechanism (where available), tsunami intensity, maximum run-up height, validity of event, warning status and some other complementary information. The tsunami data can be retrieved by area, date, source magnitude and tsunami intensity. The information can be output in summary (condensed) or detailed (expanded) form.

3) BATHYMETRY database contains the digital bathymetry on the regular grids. This database has a hierarchical structure which consists of three main levels. The first level contains the bathymetry for the whole Pacific on a 5-minute grid. These data are used for computation of trans-Pacific tsunamis and for visualization of observational data on small-scale maps. The second level contains the regional bathymetry data on a 1-minute grid which are used for computation of regional tsunamis. The third level contains the most detailed data on coastal and bottom relief on 0.1-0.01-minute grids. They are available only for some particular areas within the region where the modeling of run-up processes and interaction of tsunamis with harbors are necessary.

4) GEOGRAPHY database contains geographical data stored as different layers such as geographical contours, isolines of depth and surface elevation, administrative and state boundaries, rivers and lakes, and main cities. The user can interactively build-up the contour background map of a selected area with any desired degree of load and detail.

USER'S INTERFACE

The ITRIS is being developed for the user who is not a professional in applied mathematics and computer science. This requirement has predetermined the development of the special user interface based on pull-down and pop-up menus having on-screen buttons for process management and on-screen windows for input and output of information. A specially elaborated graphical shell provides the ability to manipulate maps, models, data and the results of computation in an efficient and convenient manner. The results of a computation can be output on the screen as graphics, histograms, isolines and vector fields which are overlaid on the real geographical maps.

Some examples of screen outputs provided by this graphic shell can be seen in Figs.1-6.

EXAMPLE OF APPLICATION

The prototype of the ITRIS has been developed for the KurilKamchatka region; however, at minimum cost it can be customized to any other region of the Pacific and elsewhere. The following example shows its application for the numerical simulation of a real historical tsunami in the New Guinea area. This is one of the more active tsunamigenic areas in the whole Pacific Fire Ring. Within two weeks in July of 1971 in the Solomon Sea there were two strong tsunamigenic earthquakes with magnitudes near 8.0. The example shows the result of the application of the ITRIS software for the simulation of the first event with magnitude 7.8 as occurred on July 14, 1971. The headpiece of the system consists of the background map of the Pacific and the main menu panel. The buttons on the panel corresponds the basic program blocks of the system. REGION opens the sub-menu for the selection of the region for numerical experimentation and construction of the computational grids. SOURCE provides the computation of initial bottom displacements for the dislocation or double-couple seismic source. WAVE - the core of the system - provides the simulation of tsunami propagation within non-linear shallow water model. TRAVEL TIMES provides fast calculation and plotting of tsunami travel times charts. DATA opens the access to the built-in historical earthquake and tsunami databases.

Fig.1 shows the submenu of the second level (the extension of the REGION button). The button CHOOSE AREA is activated and provides the selection of an area for numerical experimentation within the region (South-West Pacific) shown in the upper left screen window. The next step is the construction of the computational grid. It is made with the help of subroutine GRID (Fig.2) which takes the initial bathymetric data from the BATHYMETRY database and constructs the grid with variable spatial steps using several parameters input by the user through on-screen windows.

The next step is the calculation of initial bottom displacements in the source area, which is made through the sub-menu SOURCE. For this simulation, we use the dimensional dislocation model of the seismic source with parameters taken from (Schwartz, Lay, Ruff, 1989). Fig.3 shows the isolines of vertical bottom displacement (within the left window). These are used as initial conditions for the tsunami propagation program. During the computation, the current wave amplitudes at the preliminary selected coastal points (shown as circles with numbers on the map of an area) can be seen in the right screen window.

The specially developed numerical algorithm, based on the socalled splitting method, provides the ability to calculate tsunami propagation even on a personal computer faster than actual travel time. For instance, this simulation on 83 minutes of propagation time takes about 45 minutes of processing time on a 20-Mhz 386 PC. If we need to obtain the tsunami travel times only, we can go directly to the TRAVEL TIME lock, which provides the capability for quick (in a matter of seconds) calculation of travel time charts and displays the list of travel times to preliminary selected points (Fig.4).

An example of computed wave forms is shown in Fig.5 for point No. 1 (near Rabaul City) along with the actual observation of this tsunami recorded by mareograph near this point.

And the last figure (Fig.6) shows 3-d view of tsunami propagation at four different moments in time. According to the historical catalog, the most serious damage during this tsunami occurred on west coast of Bougainville Island (island on the right) where highest run-up (up to 6.5 meters) was observed. One can see that the numerical model, in general, reproduces this feature.

FUTURE DEVELOPMENT

The future development of the ITRIS supposes its specialization in three basic directions:

(1) facilitating the decision-making process at the regional Tsunami Warning Centers (TWC),

(2) education and training of the personnel of TWCs as well as other officials responsible for the tsunami mitigation efforts,

(3) automatization and facilitation of numerical experiments in tsunami research and investigation.

The design goal for the first application is the development of the Tsunami Expert System (TES) which can facilitate the decision making process in the emergency mode in the regional TWCs thorough integration of various types of observed data, mathematical models and intensive application of formalized expert knowledge in this field. In the operational mode, the expert system integrates all relevant information in order to evaluate the immediate tsunami threat and to suggest appropriate actions for the duty personnel. In the pre-event mode, the system allows investigation of the potential tsunami impact within the area of responsibility and provides realistic model data for planning appropriate emergency actions.

Within the second application, the design goal is the development of the Computer Aided Device for Education and Training (CADET) which will provide the possibility of numerical simulation of various warning situations within particular regions. At tsunami warning centers, the CADET system can be used for the development and playback of possible scenarios of tsunami actions within their regions of responsibility and for routine training of the duty personnel for emergency operations. At governmental and non-governmental agencies responsible for tsunami mitigation efforts, the system can be widely used for in-depth education and orientation of officials, for public demonstrations and for preevent emergency planning.

The third application of the ITRIS development foresees the elaboration of the Interactive Tsunami Modeling System (ITMS) which can be used as an advanced computer-aided tool by scientists who are not professionals in applied mathematics or computer science but who need to do some numerical experiments in tsunami research and investigation. It will provide some standardized software for tsunami modeling combined with extensive databases and efficient data processing algorithms embedded inside the convenient user shell. The system will have its basic application in tsunami research centers, and its main product will be the formalized expert knowledge applicable for tsunami risk assessment and mitigation.

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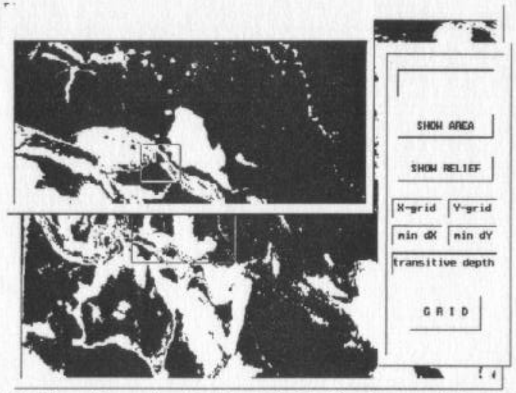

Fig.1. Selection of the region (Southwest Pacific) for the numerical experiment. Using the moving screen window shown in this example within the Solomon Sea the user can select an area for tsunami simulation and retrieve bathymetric data from the regional data base.

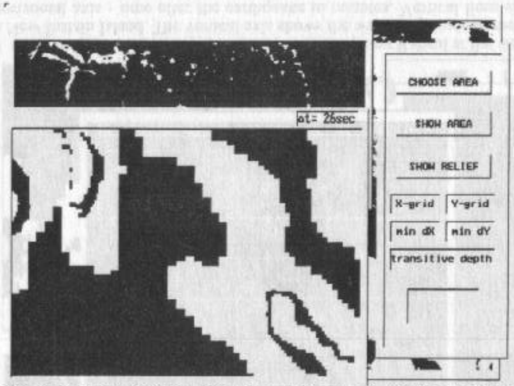

Fig.2. The area in the Solomon Sea selected for the numerical experiment. The program AREA retrieves bottom topography from the bathymetric database and constructs a computational grid with parameters to be input through on-screen windows on the right menu panel.

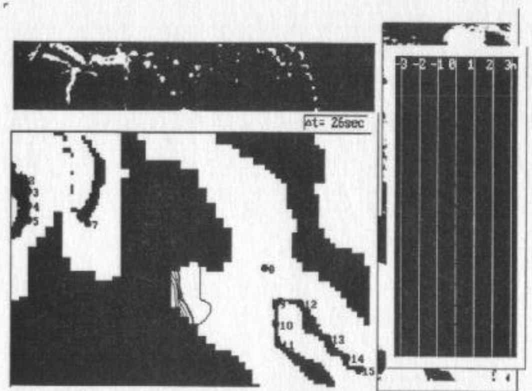

Fig.3. The vertical static displacements of the ocean bottom calculated by the subroutine SOURCE for the source parameters of the 1971 (July 14) event which were taken from (Schwartz et al, 1989). On the right - the current distribution of tsunami wave heights at the selected points indicated by the circles on the map in the left screen window.

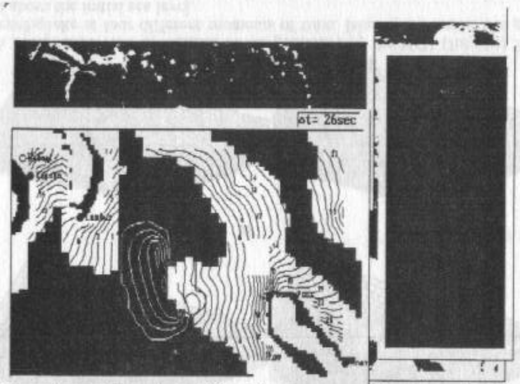

Fig.4. Tsunami travel time chart obtained for the source with parameters of the 1971 (July 14) Solomon Sea tsunamigenic earthquake (Ms = 7.8). Digits near the isolines show the travel time in minutes. The list of travel times of the front wave to the preliminary selected points is shown in the right screen window.

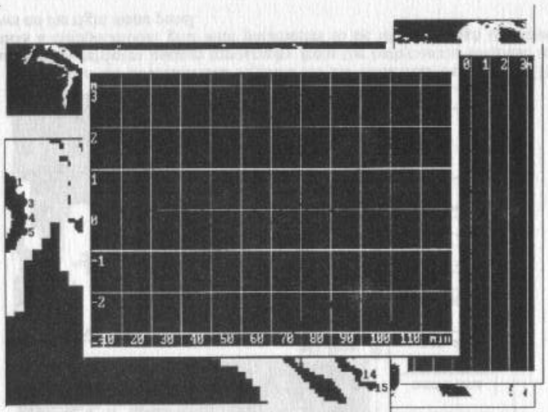

Fig.5. Computed wave form at point number 1 located near Rabaul at the west coast of he New Britain Island. The vertical axis shows the wave amplitude in meters and the horizontal axis - time after the earthquake in minutes. Vertical lines show the actual observations of wave heights.

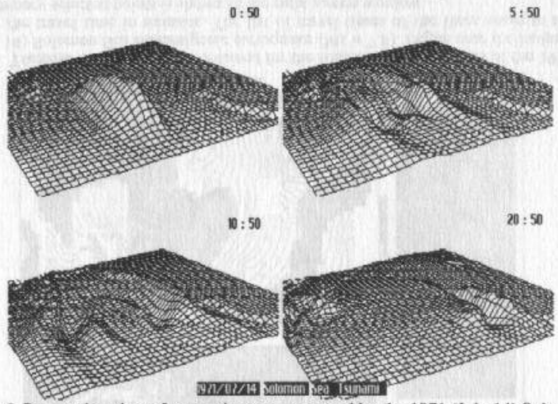

Fig.6. Perspective view of tsunami waves generated by the 1971 (July 14) Solomon Sea earthquake at four different moments of time. Islands are marked in gray and lifted above the initial sea level.