CONTRIBUTION OF THE LATE PROFESSOR CHIAKI GOTO TO TSUNAMI NUMERICAL SIMULATION

NOBUO SHUTO*, HIDEO MATSUTOMI**, KOJI FUJIMA***, FUMIHIKO IMAMURA**** AND HIROYUKI IWASE*****

PREFACE

Professor Chiaki Goto began his tsunami study under the supervision of Prof. Nobuo Shuto in 1976 when he entered the graduate course in civil engineering, Chuo University, Tokyo. He moved with his professor to Tohoku University later and developed the numerical simulation technique with the Staggered Leap-Frog Method that is now widely used in the world. He worked in Tohoku University, Port & Harbor Research Institute and Tokai University, always at the front of tsunami research.

To our sharp regret, he passed away at the age of 49, on January 8, 2002. If we follow the course of his research, we follow the history of development of tsunami numerical simulation technique. It is the aim of the present authors to select and arrange his papers on numerical technique of tsunami analysis, thus showing the short history of the development and the direction of development in the near future.

1. SIMULATION WITH THE LAGRANGIAN COORDINATE SYSTEM

Hydrodynamic equations usually used are given in the Eulerian description, with the space coordinates, and are not adequate to express the movement of tsunamis on land, the area where no water is at the initial moment. The run-up front of a tsunami, which is the most important from the viewpoint of practical application for disaster prevention, can not be exactly solved and we have to introduce an approximate moving boundary condition, except for a case where the Carrier-Greenspan transform (1958 [1]) is applied.

If we use equations in the Lagrangian description, with the material coordinates, the run-up front is given by the movement of a water particle that is on the shoreline at the initial moment. The difficulty stated above is, thus, easily solved, but at the same time, another difficulty, non-linear external force terms, is introduced. Shuto and Goto (1978 [2]) introduced the linear long wave equations in the Lagrangian description. They compared the numerical results with a theoretical solution. This is the beginning of the accuracy examination of numerical results. Goto (1979 [3]) introduced non-linear long wave equations in the Lagrangian description and showed numerical examples.

Goto and Shuto (1979 [4]) used their linear long wave equations in a practical case, the run-up simulation of the 1896 Meiji Great Sanriku tsunami in Okkirai Bay, Iwate.

Goto and Shuto (1983 [5]) numerically solved the one-dimensional run-up problem

* Iwate Prefectural University
** Akita University
*** National Defense Academy
**** Tohoku University
***** Echo Corp.

with the equations in the Lagrangian and Eulerian descriptions and compared them with the theoretical solution. The Lagrangian solution did always give sufficiently accurate results while the Eulerian solution showed a strong dependence on the size of space grid. Or, in other words, if a numerical simulation with the Eulerian equations that are more convenient is well designed, the result will be accurate enough for practical application.

2. STAGGERED LEAP-FROG METHOD FOR LINEAR AND NONLINEAR LONG-WAVE EQUATIONS

2.1 Introduction

The Staggered Leap-Frog method is now widely used in numerical simulation with linear and nonlinear long wave equations. In early 1980s, the method was established and since then many experiences were accumulated. It is one of the explicit methods, needs short computation time and simulates well run-up motion if an adequate moving boundary condition and bottom roughness are given (See for example [6]).

The Leap-Frog scheme is the central difference of the second order. The grids are staggered so as that the output points for discharge do not coincide with those for water level (See for example, [7]).

The space grid is taken variable, coarse in the deep sea and fine in the shallow sea. In a computation developed by Goto, the length of the finer space grids are made 1/3 that of the coarser space grids at the boundary of grid connection, for example, 5400m in the deep sea, then set as 1800m, 600m, 200m and so on. The time step is designed as a constant to satisfy the CFL condition for stability throughout the region of computation.

The linear long wave equations are used in the deep sea, and are switched to the nonlinear long wave equations, the shallow-water theory, in the shallow sea and on land.

2.2 Boundary conditions on land and offshore

In case of a rough estimation of run-up height, in which the detailed motion on land is not required, a vertical wall is assumed in place of the real beach, for example at the point 10m deep. Horizontal water discharge is set zero at the wall in this approximate computation.

For an exact simulation, the actual land shape should be taken into computation. With the equations in the Eulerian description, a moving boundary condition is necessarily introduced. The convenient and frequently used boundary condition is as follows. If the water level in the seaward cell is lower than the ground level in the next landward cell, discharge through the boundary between the two cells is set zero. If the former is higher than the latter, the discharge is computed with the equation of motion. To ensure the accuracy, grid size should be determined carefully (See Section 2.4).

At an offshore open boundary usually set in the deep sea, a tsunami freely propagates, without reflection, into the outside area. The wave on the boundary is assumed to propagate with the celerity of linear long waves in deep sea. Its direction of propagation is estimated with the method of characteristics, by using the water discharge in the cell adjacent to the offshore boundary.

Another offshore boundary computation is to assume a perfect reflection at a virtual vertical wall at the boundary. Half the computed wave is considered as the wave propagating outwards. If an outside grid, the length of which is designed to satisfy that the Courant number is equal to unity, is virtually introduced, the computation accuracy is much improved (Imamura et al. 2001 [8]).

2.3 Truncation error evaluation

Imamura and Goto (1988 [9]) applied the Leap-Frog scheme, Crank-Nicholson scheme and 2-step Lax-Wendroff scheme to the linear theory for long waves in a one-dimensional channel of horizontal bottom. They obtained exact solutions of these difference equations and discussed the characteristics of possible numerical errors (see Fig.1).

All the three equations have the effect of numerical dispersion. Frequency dispersion caused by the truncation error makes higher frequency components propagate slower. With the Leap-Frog scheme, larger numerical dispersion occurs in case of a small Courant number when the size of time step is small, in other words, when the number of computation with respect to time increases. Under the same condition, the 2-step Lax-Wendroff scheme and the Crank-Nicholson scheme yield larger numerical dispersion than the Leap-Frog scheme. In addition, the 2-step Lax-Wendroff scheme introduces numerical dissipation, too.

It is concluded that the simple Leap-Frog scheme with a large Courant number but not larger than unity yields better numerical results in the analysis of the linear long waves without dispersion.

A reverse use of the numerical error in place of a physical term is described in 3.2.

2.4 Length of space grid

Numerical error depends on numerical scheme, wave profile, wave-grid length ratio $L/\Delta x$ and so on. The following discussion assumes the Leap-Frog scheme.

Shuto et al. (1986 [10]) systematically carried out numerical experiments for linear long waves on a one-dimensional channel of

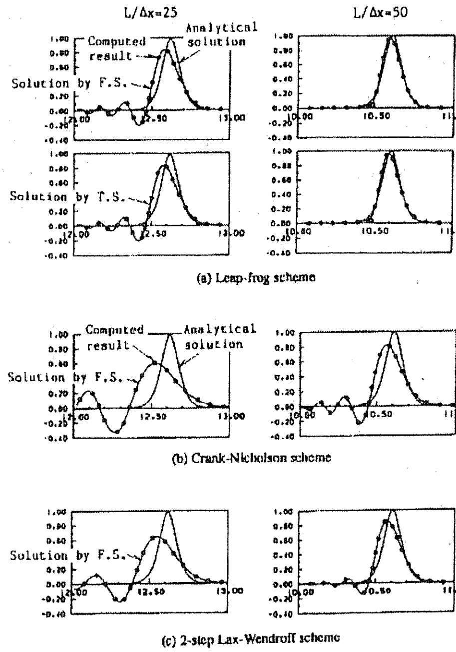

Fig. 1 Comparisons of numerical solution and theoretical solution (Imamura and Goto, 1988 [9]).
The left figures show the results for the case $\Delta x/L = 1/25$, after propagation over 4 wavelength. The right figures show the results for $\Delta x/L = 1/50$ after propagation over 8 wavelength. The Courant number is 0.5 for all cases.

horizontal bottom. Their criteria of judgment is that the difference in computed wave height should be less than 5% after a wave travels over a distance of four wave length. They found $L/\Delta x$ should be not smaller than 20, that is, a wavelength L should be covered by more than 20 grids.

If we follow this criterion, the next problem is how to take the wavelength L. Imamura and Goto (1988 [9]) compared the 1986 Meiji Great Sanriku Tsunami and the 1964 Alaska Tsunami. They found that the former needed 15 grids per wavelength while the latter 150 grids, if the wave height remained within 10% difference after a travel over the distance of one wavelength. The initial wave profile of the former was determined from seismic data that could not estimate high frequency components, while that of the latter that was determined field survey did include high frequency components as shown in Fig.2 . The wavelength L should be taken to be the wavelength of the component that a modeler wants to simulate with sufficient accuracy.

In a simulation, space grids have different size, coarse in the deep sea and fine in the shallow sea as stated in 2.1. At the boundary connecting the grids of different length, data obtained for the coarse grids are linearly interpolated to yield data for the fine grids. This interpolation introduces deterioration of numerical results. In case of a simple sinusoidal wave, $L/\Delta x$ should be not smaller than 30 to 60 so as that the error is less than 5% (Goto and Sato, 1993 [11]).

Tsunami run-up needs another consideration. Goto and Shuto (1983 [5]) obtained $\Delta x/(gmT^2) \le 4 \times 10^{-4}$ in order that the run-up height be estimated within an error less than 5%, where m is the inclination of slope, T the wave period and g the gravitational acceleration.

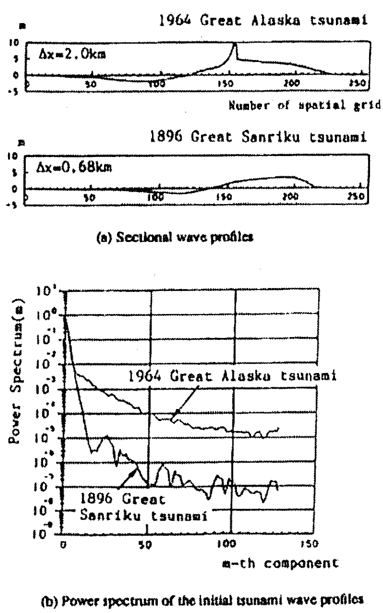

Fig. 2 Initial tsunami profile and power spectrum of the 1964 Alaska tsunami and the 1896 Meiji Great Sanriku tsunami (Imamura and Goto, 1988 [9]).

Refraction on a uniform slope was discussed by Sayama et al. (1988 [12]). Results with the Leap-Frog method underestimates the refraction effect, and almost equal to the results of an approximation in which an exact theoretical curve is expressed by broken straight lines in each grid. Comparing the exact and approximate solutions of the wave-ray equation, they showed a relationship between the final accuracy and the length of space grid (see Fig.3).

In case of a conical island, Fujima et al. (2000 [13]) proposed that $\sqrt{gmr_0}T/\Delta x$ be larger than 300, in order that the highest run-up is simulated within an error of 10%, where r_0 is the radius of the island shoreline and $\sqrt{gmr_0}T$ a parameter relating the wavelength of trapped mode.

2.5 Bottom friction and others

2.5.1 Bottom friction

The bottom friction is often expressed by the Manning formula as $\tau_b = \rho g n^2 h^{-1/3} u|u|$, where n is the Manning's roughness coefficient, ρ the dencity, g the gravitational acceleration, h the water depth and u the current velocity. Originally, n is defined and given for steady flow. Fujima et al. (2002 [14]) examined whether or not a similar idea is applicable to linear long waves. For a fully developed boundary layer, they gave $n = 0.15k_s^{1/6}/\sqrt{\ }$, where ks is the equivalent grain size. For example, n = 0.015 for k_s = 1 mm and n = 0.033 for k_s = 10cm. Their formula is similar to the Manning-Strickler formula with 10% difference. Values of n that have been successfully applied to steady flow,

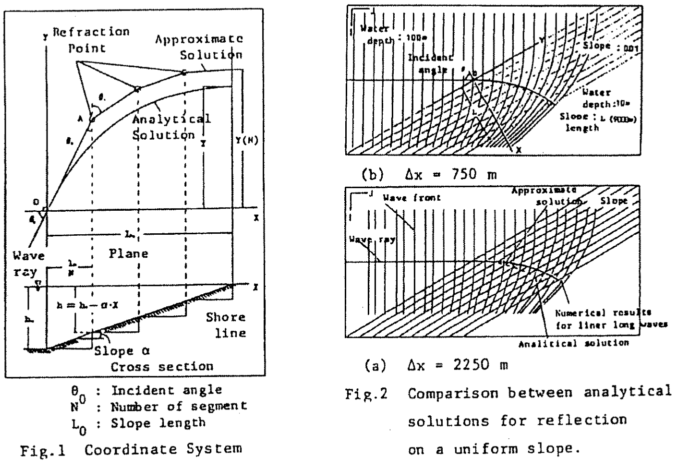

Fig. 3 Wave–ray refracted on a uniform slope (Sayama et al. 1988 [12]).

therefore, provide a good reference for unsteady flow. In a tsunami simulation, n is often assumed to be about 0.025. The value of n is made larger as the water depth becomes shallower.

2.5.2 Drag force of buildings

Resistance of large obstacles such as buildings is mainly due to form drag. Goto and Shuto (1983 [15]) carried out hydraulic experiments of a grouped–building model by using a steady flow in an open channel. The form drag coefficient is a function of the Froude number and the contraction ratio in the entrance region, that of the Froude number and the expansion ratio in the rearmost region, and that of the Froude number alone in the region between the two. Once these drag forces are evaluated, an equivalent n is determined so as to give the same energy gradient. Then this equivalent n is used in the simulation, thus the form drag in the actual field being transformed to a virtual bottom friction.

2.5.3 Tsunami control forest

Effect of tsunami control forest was considered by Aburaya and Imamura (2002 [16]), in terms of the drag and virtual mass coefficients according to the actual forces, not transforming them into roughness coefficient.

2.5.4 Entrance gap of breakwaters

Similar idea to Section 2.5.2 can be applied to the energy loss due to the rapid contraction and expansion at the entrance gap of breakwaters. An actual flow shows non–uniform current of large turbulent motion at the gap. With the shallow–water theory, these effects cannot be fully simulated, even if very fine space grids are distributed near the breakwaters. This leads to a modification of n. Goto and Sato (1993 [11]) showed that a coefficient of momentum loss 0.5 should be assumed at the gap in order to make the computed results equal to the results of hydraulic experiments, in a design effort of the tsunami breakwaters in Kamaishi Bay, Iwate.

2.5.5 Flow over breakwaters

When a tsunami overflows structures, the Homma formula (1949 [17]) is often used to determine discharge. The actual flow may be different from the formula given for steady flow, in which the overflowing water depth is only the major factor. A tsunami is unsteady flow. In particular, if a tsunami overflows as a breaking bore, the discharge may differ from that obtained from the Homma formula. Mizutani and Imamura (2002 [18]) showed that the discharge for a bore-like tsunami is more than twice that of the Homma formula.

2.6 Damage assessment

The fundamental data necessary to estimate damage due to tsunami is the flooded area and the arrival time of tsunami. Since water level and discharge are computed at every time step over the whole area of computation in a numerical simulation, these information is easily output. Kotani et al. (1998 [19]) used this output to estimate possible damage, by referring the conditions of damage to houses and of loss of lives. Loss of lives, however, should be examined more carefully because it depends very much upon how coastal residents react and evacuate.

Lumbers, once floated and transported by tsunamis, have considerably bigger impact than tsunamis themselves to destroy coastal cities. Goto et al. (1982 [20]) and Goto (1983 [21]) assumed that lumbers does not affect the movement of water, since the length of lumbers is shorter than the length of one space grid. The computed current velocity for a computation cell is the averaged value in the cell and is obtained on neglecting actual complex current distribution inside the cell. Lumbers are actually moved and spread by the complex current system, while the center of cluster of lumbers is moved by the computed current. In order to describe the spread of lumbers, Goto et al. (1982 [20]) used a diffusion coefficient, $0.032u_*h$, determined from hydraulic experiment, where u_* is the shear velocity on assuming the logarithmic velocity profile and h the water depth. Another evaluation of the diffusion coefficient, $0.21u_*h$, was given by Nakagawa et al. (1983 [22]). The difference between the two needs more consideration in the near future.

To compute unsteady motion of a lumber, the form drag and virtual mass coefficients are needed. Goto et al. (1982 [20]) obtained the drag coefficient from hydraulic experiments and the virtual mass coefficient from the potential theory.

Once the collision velocity of a lumber is computed, impact of the lumber is evaluated with the experimental results of Matsutomi (1999 [23]).

Inflammable materials such as oil may cause a devastating effect if spread by a tsunami and if caught by fire. Goto (1985 [24], 1990 [25]) developed a method to solve the spread of oil. He solved two sets of equations simultaneously, one for water and another for oil. The resistance coefficient on the water-oil interface, $f = 0.2 / R_e$ is recommended, where $R_e = U_0 D_0 / \nu$, U_0 is the horizontal velocity of oil, D_0 the thickness of oil and ν the oil viscosity. His method can be applied to the gravity-inertial and gravity-viscous regimes of oil spread.

2.7 Curvilinear coordinates

If a modeler uses the ordinary Cartesian coordinates to simulate a tsunami in a river, he may be bothered by reflections from indented river-bank. Introducing a curvilinear coordinate system as Goto and Shuto (1981 [26]) used, he can solve this phenomenon although it is not easy to select an adequate curvilinear coordinate system for a complicated river network.

If a tsunami or a flood spreads over a plain, small difference in topography sometimes causes a big difference in numerical results. Yasuda et al. (2001 [27]) introduced a new method to express topography, Adaptive Grid for Topography, with which topography is better approximated and the number of grids is much decreased.

3. MODELS FOR LINEAR AND NON-LINEAR DISPERSIVEWAVES

3.1 Dispersion effect in tsunami

There are three cases where the dispersion effect is not negligible. The first and second cases can be explained with the linear frequency dispersion. According to Iwase et al. (2002 [28]), the initial profile, the water depth of source area and the travel distance determine whether the dispersion effect is necessary or not. The third case is explained with the non-linear effect and the linear frequency dispersion.

The first case is a distant tsunami, for which the initial profile and the travel distance are important factors. Different wave components of an initial profile propagate with different celerity depending on their frequency. Even if the difference is very small, wave profile changes during a long travel. Behind the leading wave, a train of waves having similar period to it appears and develops. The linear long wave theory with dispersion should be applied for the Kajiura number $p_a > 4$ (Kajiura, 1970 [29]), a parameter related to the dimension of the source, the distance from the source and the depth of water.

The second is a near-field tsunami; in which similar phenomenon as above may occur behind the leading wave even if the travel distance is short. A qualitative analysis can be done by comparing weights of the dispersion term to the linear term on assuming sinusoidal waves (Shuto, 1976 [30]). Iwase et al. (2001 [31]) found that in case of the 1983 Nihonkai Chubu earthquake tsunami, the dispersion term was necessary

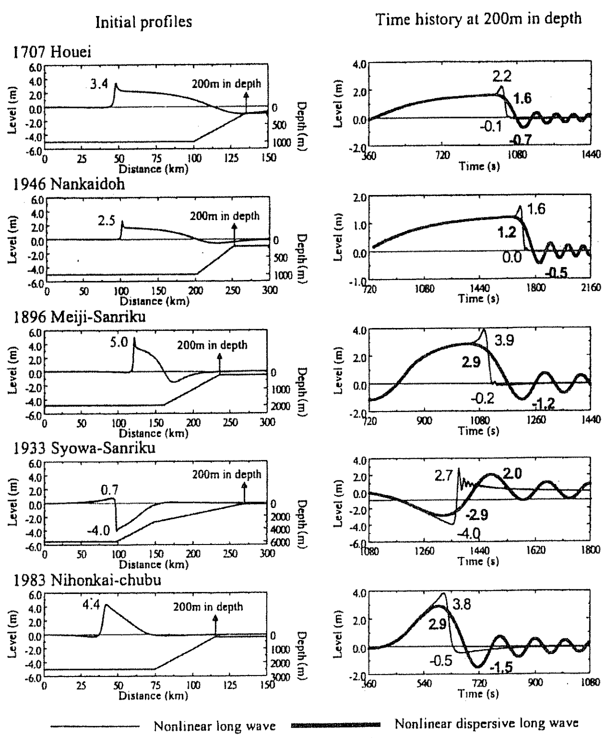

Fig. 4 Dispersion effect on near-field tsunami discussed by Iwase et al. (2002 [28]).

because of its particular initial profile, although the source was not far from land (see Fig.4).

Iwase et al. (2002 [28]) carried out the detailed analysis and introduced a parameter I_D, originally expressed with the strength of power spectrum components of the initial profile and the difference of their celerity from the linear long wave celerity. A simple expression of I_D is also given in terms of the fault width, dip angle and mean depth of the source area. For $I_D > 1$, the dispersion effect is not negligible.

The third is a tsunami in shallow sea and rivers. The front of a tsunami becomes steeper due to the non-linear effect, and then a train of short waves similar to wind waves and swell evolves and develops at the tsunami front. This phenomenon is usually called as soliton fission or undular bore.

3.2 The first case —Dispersion equations for a distant tsunami—

The linear Boussinesq is applied to this case. This equation is different from the original Boussinesq equation because it does not have the non-linear terms. This is also different from the linear long wave equation because the latter does not include the physical dispersion term.

Imamura and Goto (1988 [9]) suggested the use of the numerical dispersion in place of the physical dispersion. As described in Section 2.3, the Leap-Frog scheme when applied to the linear long wave equations introduces numerical dispersion. If the grid length is selected to satisfy that the Imamura number is equal to unity, the numerical dispersion has the same effect as the physical dispersion (Imamura, 1989 [32]). This process has another advantage. In place of an implicit scheme required to solve the linear Boussinesq equation, the Leap-Frog scheme, an explicit scheme is applied to the linear long wave equation.

Sayama et al. (1987 [33]) discussed the two-dimensional case. They showed that the addition of numerical dispersion to physical dispersion led to highly accurate simulation.

3.3 The second case —Dispersion equations for a near-field tsunami in deep sea—

Several dispersion equations are proposed for non-linear long waves. Even if the order of approximation is the same, the different derivation process leads to different results in the magnitude of dispersion. For example, the Peregrine equation (1967 [34]) is given in terms of a sectionaveraged horizontal velocity, while the Madsen-Sorensen equation (1992 [35]) in terms of total discharge in a section. Iwase et al. (1998 [36]) rewrote the Peregrine equation by changing the variable from the section-averaged velocity to the section-integrated discharge. This is called the modified Peregrine equation hereafter. Goto (1984 [37]) introduced a non-linear dispersive long wave equation applicable for a large Ursell number (see Fig.5). When the non-linear dispersion is omitted and the bottom is assumed horizontal, it is called as the simplified Goto equation.

Iwase et al. (2002 [38]) compared eight non-linear long wave equations in terms of linear celerity. For the water-depth-to-wave-length ratio $h/L < 0.1$, there is no difference among the eight equations. The Peregrine equation, the modified Peregrine equation, and the simplified Goto equation give less than 1 % error from the linear surface wave celerity for $h/L < 0.16$. The Madsen-Sorensen equation is found the best for $0.1 < h/L < 0.5$ among the eight. Some of equations become unstable for $h/L > 0.5$, and should not be used if high wave components in an initial profile is not negligibly small.

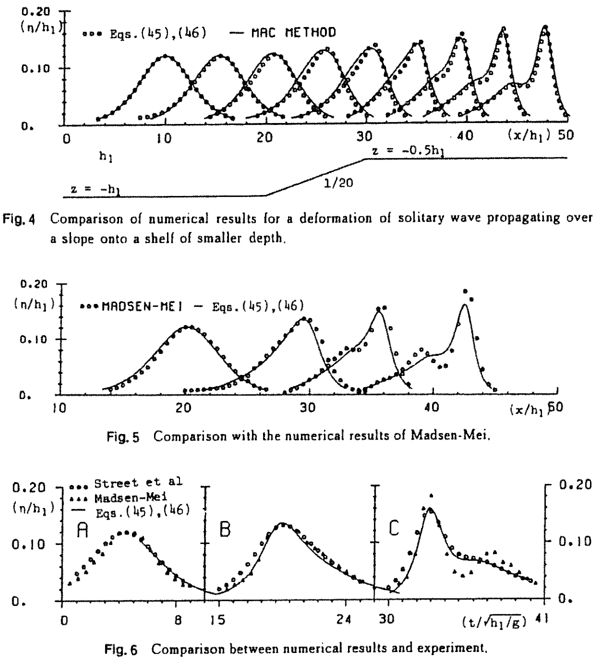

Fig. 5 Reproducibility of Goto equation (1984 [37]). The upper and middle figures show the comparisons with the MAC method and Madsen–Mei equation, respectivity. The bottom figure shows the comparisons with the experiments of Street et al. The location A, B and C is $x/h_1 = 14.65$, 30.0 and 41.6, respectively. In these figures, 'Eqs.(45) and (46)' indicate the Goto equation.

3.4 The third case —Soliton fission—

Iwase et al. (2002 [30]) discussed by taking the celerity of solitary wave given by the Kortewegde Vries equation as the standard and also by comparing the computed wave profiles with the results of hydraulic experiments. The Boussinesq equation, the modified Peregrine equation and the Madsen–Sorensen equation are recommended from the comparison of wave celerity. By comparing with the hydraulic experiments of soliton fission, the modified Peregrine equation is slightly better than the Madsen–Sorensen equation.

3.5 Difference scheme

Goto et al. (1988 [39]) used the Leap–Frog scheme to express the linear Boussinesq equation given in terms of discharge. In case of a tsunami propagation over the Pacific Ocean, Imamura et al. (1990 [40]) expressed the linear Boussinesq equation including the Coriolis force by the longitude–latitude coordinates. They solved the difference equation of motion implicitly. In case of the two-dimensional equation, equations of motion in the x– (longitude) and y– (latitude) directions are simultaneously solved.

Iwase et al. (1998 [36]) introduced a new algorithm, the two-step mixed finite difference scheme, into the computation of the non-linear long wave equation with dispersion. At the first step, the equation including the local acceleration, convection and static hydro-pressure terms is explicitly solved with the Leap-Frog scheme, and at the second step the equation including the local acceleration and the dispersion term is implicitly solved. The Leap-Frog scheme if applied to the linear long wave equation yields the numerical dispersion as the truncation error. The upwind difference if applied to the non-linear convection term yields the numerical dissipation as the truncation error. These truncation errors at the first step are included in the second step, to reduce their effects. Thus, their method promises high accuracy of the result. Comparison with hydraulic experiments also ensured the accuracy of their method. This method is applicable to the practical simulation of tsunamis in the sea and on land, similarly to the case of the non-linear long wave theory. Iwase et al. (2002 [41]) successfully applied this scheme to the run-up problem of the 1983 Nihonkai-Chubu earthquake tsunami.

With this scheme, equations of motion in the x- and y-directions can be solved separately and the computation time is considerably reduced. The 2-step mixed finite difference scheme has the same advantage as the ADI scheme. At present, the Iwase et al' scheme is the best method applicable to the practical simulation of linear and nonlinear dispersive long waves, without instability and with the least numerical error as shown in Fig.6. If the space grids much finer than those in the present use are considered, the implicit scheme introduced by Imamura et al. (1990 [40]) is recommended (Fujima and Goto, 2003 [42]).

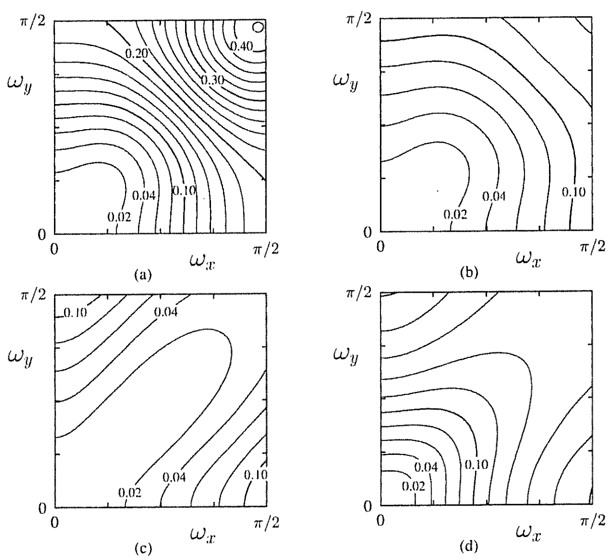

Fig. 6 Truncation error of linearized Boussinesq equation obtained by Fujima and Goto (2003[42]). The contour lines of $(c_b - c)/c_o$ are drawn for $c_o \Delta t / \Delta x = c_o \Delta t / \Delta y = 0.7$, $h/\Delta x = h/\Delta y = 0.6$, where c_b = theoretical celerity of differential equation, c =celerity of difference equation and $c_o = \sqrt{gh}$. In these figures, $\omega_x = k_x \Delta x / 2$, $\omega_y = k_y \Delta y / 2$ and (k_x, k_y) = wave number. (a) explicit scheme, (b) 2-step mixed finite difference method proposed by Iwase et al. (1998 [36]), (c) Leap-Frog implicit scheme proposed by Imamura and Goto (1990 [40]), (d) Crank-Nicholson implicit scheme

3.6 Breaking solitons

A non-linear long wave equation with dispersion can simulate soliton fission and evolution. After fully developed, solitons begin breaking from the leading soliton, reduce their heights, and redevelop again because momentum is supplied from behind. Except for the momentum supply in this process, breaking and decay are not included in the equation. Additional conditions should be added from the viewpoint of real physics, by referring hydraulic experiment. The breaking condition is introduced in terms of H/h, or in terms of u/C, where H is the wave height, h the water depth, u the horizontal velocity at the crest of wave and C the celerity. The decay is expressed in terms of eddy viscosity. Another consideration is sometimes required to locally improve the degree of approximation of the equation.

Iwase et al. (2001 [43]) discussed this problem for non-linear long waves in a channel of horizontal depth with the Madsen–Sorensen equation, by comparing hydraulic experiments with numerical simulation. First, they introduced an artificial diffusion term to express the rapid growth in a nearby region of wave crest satisfying $H/h > 0.6$, where a higher approximation than the Madsen–Sorensen equation is locally needed. Secondly, the maximum height is determined from $u/C = 0.71$. Thirdly, an eddy viscosity related to the total water depth and water level is assumed to express the decay of solitons.

This is an attempt to simulate the process. The problem requires further study in the future.

4. 2D / 3D HYBRID MODEL

The long wave approximation begins with an assumption that the horizontal velocity is vertically uniform in a section. Even if the order of approximation is increased, it is quite difficult to include the complicated three–dimensional flow around and near a structure. A three–dimensional model is required. However, the model is only needed in the neighborhood of the structure, not in the other area. This leads to an idea of 2D/3D hybrid model that connects the two–dimensional long wave equations and a three–dimensional model, the former being used in the wide area and the latter in the neighborhood of the structure.

Fujima et al. (2001 [44], 2002 [45]) proposed a method and compared with hydraulic experiments in case of a tsunami breakwater. The gap at the entrance is made narrow and shallow in order to reduce the seawater discharge into the sheltered area. Their model could simulate well three–dimensional structure of flow at the gap, although the turbulence model included needs more refinement.

Similar consideration is applicable to such a case of the highest run–up of the 1993 Okuhiri tsunami. It was found in a small valley at Monai. On the coastal cliff at the entrance of the valley 50m wide, runup was 23m, and the highest 32m was measured at the bottom of valley 50m far from the entrance. The valley has a very steep bottom that made the vertical movement of the tsunami non–negligible. With such a 2D model as the shallow–water theory, no one could simulate this rapid change of tsunami runup. Yoneyama et al. (2002 [46]) applied a 3D model to the limited area near the valley and could simulate well run–ups in and in the neighborhood of the valley. A combination of 2D and 3D models, that is, a 3D model in the particular area and a 2D model in other area will be a reasonable method to cover the whole area of computation.

5. CONCLUDING REMARKS

The late Professor Goto was hospitalized in May 2000, suffering a stomach cancer. After an operation, he recovered rapidly, left the hospital and came back to research and education. In April 2001, he relapsed and continued a fight in the hospital against the cancer until January 2002. Even during this period, he showed an incessant passion and concern of tsunami research. He heard the research results from students and gave them advice in his sickroom. On the sick bed, he hand-wrote manuscripts of research papers and planned the research idea in the future.

It is the wish of the present authors that this short memorandum stimulates young researchers to follow him and make them continue tsunami research, as he did, step by step, examining the numerical technique with physical and theoretical results.

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