# Tsunami Simulation for Capacity Development

Su Yean Teh and Hock Lye Koh

*Abstract*—**The 26 December 2004 Andaman mega tsunami killed about 200, 000 people worldwide. This infamous tsunami serves a potent wakeup call for many countries in the affected regions including Malaysia, Thailand and Indonesia. More recently, the 25 October 2010 tsunami in Mentawai islands of Indonesia that killed more than four hundred people is a recurrent reminder of the hazards of tsunamis in this region. Active research on tsunami simulation and community outreach activities on tsunami education, risk reduction and preparedness are essential to help community develop resilience to tsunamis. Many researchers in the regions have developed their respective long-term programs on tsunami related research for this purpose. Over the past several years, capacity building has been intensely stepped up to develop human resources that are able to perform tsunami simulations for developing inventory of tsunami risk hotspots and evacuation routes. Several international workshops were held in the Indian Ocean and South China Sea regions to propel effective research collaboration. Enlightened by these international workshops, the Malaysian government has appointed the authors to (a) develop tsunami simulation model TUNA, (b) to establish local maps that rank tsunami risk hotspots and their associated characteristics for northwest Peninsular Malaysia and (c) to conduct tsunami modelling workshops for the purpose of developing human resources capable of performing or understanding tsunami simulations in their respective work place. This paper presents an overview of tsunami simulations performed by means of the model TUNA for the recent tsunamis that occurred in Andaman Sea and the South China Sea to highlight potential hazards. It also provides a summary of tsunami simulation training manual based upon TUNA to facilitate effective hands-on learning on tsunami simulation.**

*Index Terms*— **Risk maps, tsunami simulation, TUNA**

## I. Introduction

The term *tsunami* is a Japanese word referring to waves that amplify their heights and velocities as they enter a harbour. It generally has a bad connotation implying impeding danger. When tsunamis propagate over shallow water, the waves amplify in heights and velocities. The waves can trigger substantial oscillations in harbours, by reflecting off harbour embankments and combining the reflected waves to form substantially larger waves. As the waves amplify over shallow water, they generate intense turbulence. Hence, tsunamis can become very dangerous when they propagate over shallow beaches or when they enter a harbour, often inflicting high human casualty. This unfortunate occurrence was vividly witnessed during the 2004 Andaman tsunami. A tsunami may be created by sudden movements or disturbances of the seafloor, or by submarine landslides, or by impacts of large objects such as asteroids on the sea surface. It can also be created by shaking of a closed basin such as a reservoir or harbour induced by earthquakes. Previously perceived as safe from the hazards and disasters of tsunami, Malaysia faced a rude awakening by the 26 December 2004 Andaman tsunami, suffering a loss of 68 people. Right after the event, a team of researchers from Universiti Sains Malaysia (USM), in collaboration with other national and international scientists, initiated sustained research on various aspects of tsunami, aspiring to develop sustainable coastal communities that are tsunami resilient. The USM team is currently active in research on numerical simulations of tsunami covering source generation, propagation, coastal runup and inundation. An ecosystem model MANHAM was also developed to assess the ecological impacts of tsunamis and mega storm surges on coastal vegetations [1, 2]. An in-house tsunami simulation model TUNA has been developed and successfully applied to simulate tsunamis originating from the Andaman Sea [3-5] and the South China Sea [6] for impact assessment and mitigation. The simulation results are carefully compiled and communicated to government agencies and communities at risk for the purpose of documenting tsunami risk maps and evacuation routes. The research has been extended to include the assessment of the role of mangrove as a mitigation measure to reduce the impact of tsunami hazards [7-9]. Following this success, the Disaster Research Nexus (DRN) was recently established in the School of Civil Engineering USM to spearhead active research on tsunamis and other natural disasters such as earthquakes.

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## II. TUNA: Tsunami Simulation Model

The propagation of tsunami in deep oceans may be simulated by the depth-averaged two-dimensional shallow water equations (SWE) as proposed by the Intergovernmental Oceanography Commission (IOC) [10]. The SWE is applicable when the wave heights are much smaller than the depths of water, which in turn are much smaller than the wavelengths. Depth-averaged 2D models are normally used for tsunami propagation simulations, as these provide adequate solution. On the other hand, three-dimensional models will lead to excessive memory requirement and long computational time. Hence, under normal assumptions typically applicable to tsunami propagations in the deep ocean, the hydrodynamic equations describing the conservation of mass and momentum can be depth averaged [11, 12] and may be written as (1) to (3).



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$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \quad (1)$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)+gD\frac{\partial \eta}{\partial x}+\frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2}=0 \quad (2)$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)+gD\frac{\partial \eta}{\partial y}+\frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2}=0 \quad (3)$$

$$\eta_{i,j}^{k+1}=\eta_{i,j}^{k}-\frac{\Delta t}{\Delta x}\left[M_{i+0.5,j}^{k+0.5}-M_{i-0.5,j}^{k+0.5}\right]-\frac{\Delta t}{\Delta y}\left[N_{i,j+0.5}^{k+0.5}-N_{i,j-0.5}^{k+0.5}\right]$$

$$M_{i+0.5,j}^{k+0.5}=M_{i+0.5,j}^{k-0.5}-gD_{i+0.5,j}^{k}\frac{\Delta t}{\Delta x}\left[\eta_{i+1,j}^{k}-\eta_{i,j}^{k}\right]$$
$$D_{i+0.5,j}^{k}=h_{i+0.5,j}+0.5\left[\eta_{i+1,j}^{k}-\eta_{i,j}^{k}\right]$$

$$N_{i,j+0.5}^{k+0.5}=N_{i,j+0.5}^{k-0.5}-gD_{i,j+0.5}^{k}\frac{\Delta t}{\Delta y}\left[\eta_{i,j+1}^{k}-\eta_{i,j}^{k}\right]$$
$$D_{i,j+0.5}^{k}=h_{i,j+0.5}+0.5\left[\eta_{i,j+1}^{k}-\eta_{i,j}^{k}\right] \quad (4)$$

$$\Delta t\le\frac{\Delta x}{\sqrt{2gh}} \quad (5)$$

Here, discharge fluxes ($M$, $N$) in the $x$- and $y$- directions are related to velocities $u$ and $v$ by the expressions $M=u(h+\eta)=uD$, $N=v(h+\eta)=vD$, where $h$ is the sea depth and $\eta$ is the water elevation above mean sea level. The shallow water equations consisting of (1) to (3) can be solved by several methods, such as the finite difference methods. The explicit finite difference method is employed in TUNA, as it is known to perform well, provided that the time step $\Delta t$ fulfils the Courant criterion. Partial derivatives are replaced by finite differences as shown in (4), while time step $\Delta t$ is restricted by the Courant criterion (5) to ensure stability of the numerical scheme. The complicated discretization of the nonlinear bottom friction and advection terms can be referred to [3]. These nonlinear terms are incorporated into TUNA with an option of bypass. The staggered scheme [10, 13-15] as illustrated by Fig. 1 is employed to solve the partial differential equations. The evolution of earthquake-generated tsunami waves has three distinct stages: generation of initial water vertical displacements at source, propagation of generated tsunami waves in deep water and final beach wave runup. There are several numerical models developed based upon the SWE (1) to (3) to simulate tsunamis propagations, for example, the model TUNAMI-N2, developed by Imamura of Tohoku University [16], and the MOST model [17]. The finite difference method is also employed in these models. Numerical testing of TUNA has been performed against known analytical solutions to ensure that it is capable of simulating tsunami propagations [18]. Simulation results with TUNA indicate satisfactory performance when compared with COMCOT [19] and validated with on-site survey results for the 2004 Andaman tsunami in Penang and Langkawi beaches [3].

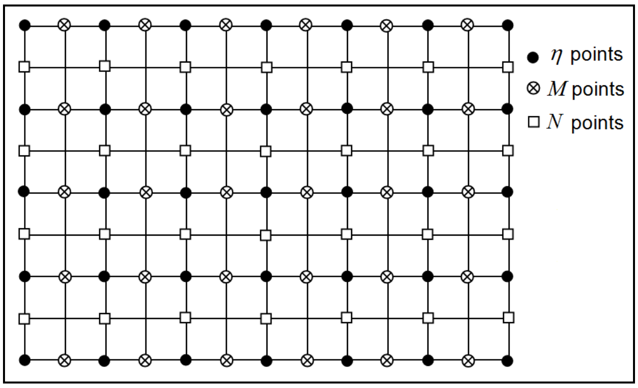


Fig. 1. Computational points for a staggered scheme.

## III. Application of TUNA

In this paper, we demonstrate applications of TUNA to simulate three recent tsunamis that occurred in the past six years in this region. The tsunami simulation model TUNA is applied to develop tsunami risk maps for potential tsunamis originating from the Andaman Sea and the South China Sea. TUNA is also applied to simulate the recent 25 October 2010 Southern Mentawai tsunami. For the 2004 Andaman tsunami, Fig. 2 shows the initial tsunami wave heights at the source off the coast of Aceh of Sumatra in the Andaman Sea. This initial source wave heights is generated by the Okada model [20], applied to the 2004 earthquake that triggered a five-segment fault extending for a length of 1200 km [21]. This five-segment fault differs from the straight-line fault of similar length, initially used by most tsunami simulations immediately after the 2004 tsunami. The uncertainty regarding fault orientation remains a major source of errors in tsunami prediction. It is therefore important to conduct sensitivity analyses to assess the impact of source uncertainty in tsunami simulation analyses in order to incorporate relevant risk factors in any evaluation of risk.

For a potential fault identified as a tsunami hazard in the South China Sea, Fig. 3 shows the initial tsunami source generated by a six-segment fault in the Manila Trench [22]. The Manila Trench is currently regarded as a major hazard exposing the South China Sea region to earthquake and subsequent tsunami risks. These two faults mentioned above are considered as the most significant tsunami hazards to coastal communities along the Indian Ocean and South China Sea. Variations in magnitude and orientation of these two faults are certainly possible, due to uncertainty in predicting earthquake characteristics that generate tsunamis. Hence, any tsunami risk maps and evacuation routes must consider these variations in tsunami sources in the evaluation of risk and exposure.

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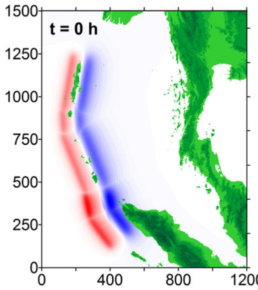


Fig. 2. Initial tsunami source for the 2004 tsunami [21].

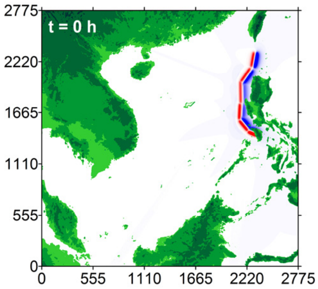


Fig. 3. Initial tsunami source for South China Sea [22].

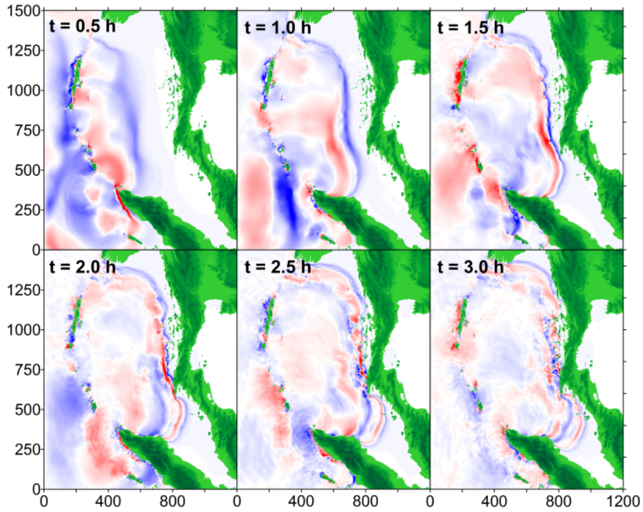


Fig. 4. Snapshots of 2004 tsunami propagation at interval of 0.5 hour.

Fig. 4 illustrates snapshots of the 2004 tsunami propagation in the Andaman Sea generated by the five-segment fault shown in Fig. 2, at interval of 0.5 hour. In the 2004 Andaman tsunami, the tsunami waves generated did not propagate directly towards northwest Peninsular Malaysia, as may be observed from the snapshots. The location and orientation of the fault caused the waves to propagate directly towards Phuket, inflicting severe casualty there. Simulated and recorded maximum wave heights exceeded 8 m along beaches in Phuket. Because of the seabed topography, part of the waves that propagated directly toward Phuket was refracted towards northwest Peninsular Malaysia, including Langkawi and Penang. This refraction of waves as they continue to propagate towards Penang and Langkawi caused the wave to reduce in strength. Hence, we conducted careful simulation analyses of the impacts of potential variations in source orientations. The results indicate that a slight clockwise rotation of the northern parts of these faults would intensify tsunami risk for the coastal regions of northwest Peninsular Malaysia and northern Thailand. A clock-wise rotation of source orientation would put some of these regions directly on the propagation path of the tsunami generated. Under this hypothetical scenario, simulated runup tsunami wave heights indicated wave heights exceeding eight meters for some beaches along the affected coasts of northwest Peninsular Malaysia, including Langkawi and Penang. The actual and simulated maximum tsunami wave heights recorded at these two locations for the 2004 Andaman tsunami varied between 3 to 4 m, depending on the locations. Hence, the potential risks caused by tsunami waves exceeding 8 m to these two locations could be as severe as those recorded in Phuket during the 2004 tsunami. Despite these potential risks to which beaches in Penang are exposed, local authority continues to approve coastal development along precisely these beaches that are most vulnerable to these tsunami risks. Perhaps the risks and vulnerability were not adequately understood by those government agencies in charge of the approval process. Hence, it becomes essential for responsible government agencies to receive training on tsunami sciences and simulation. For this purpose, the last section of this paper on tsunami simulation training is written.

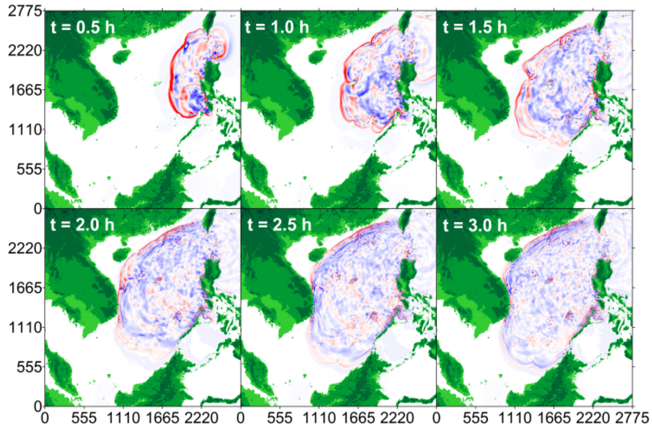


Fig. 5. Snapshots of tsunami propagation in South China Sea at interval of 0.5 hour.

We now return to the issue of tsunami threats in the South China Sea. Fig. 5 illustrates snapshots, at interval of 0.5 h, of the potential tsunami propagation generated by the six-segment fault located in the Manila Trench in the South China Sea shown in Fig. 3. The Island of Hainan, Hong Kong and the coasts of Vietnam are directly exposed to potentially high tsunami waves originating from the Manila Trench. As for the coasts of Sabah, the risks appear to be somewhat mitigated by the presence of the Palawan Islands. These islands deflect the tsunami waves to run parallel to the coast of Sabah, instead of heading directly towards Sabah in the absence of the Palawan islands. However, other tsunami threats posing severe hazards to Sabah and Sarawak still remain. One such threat might come from submarine landslides off the coast of Brunei [23] and the Manila Trench. Another source of potential tsunami might be located in the Sulu Trench south of the Manila Trench that might trigger tsunamis that propagate directly towards Sabah. It is therefore important for coastal community in these regions to remain vigilant, and for the tsunami scientists to continue to be on guard. The following section describes the most recent tsunami simulation for the Mentawai islands tsunami.

On 25 October 2010, an earthquake of magnitude 7.7 occurred near South Pagai Island in the Mentawai Islands Region of Indonesia at 14:42UTC. The earthquake generated a series of tsunami waves that struck the shores of Mentawai islands with reported tsunami wave heights of 3 to 7 m within fifteen minutes after the earthquake. Although the number of lives lost in this recent Mentawai event (~400 deaths) pale in comparison to those of the 26 December 2004 event (~200, 000), the Mentawai event sparked off debates on the effectiveness and the efficiency of the early

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warning system set up in the Indonesian region after the 26 December 2004 tsunami. The Pacific Tsunami Warning Centre in Hawaii did issue a tsunami warning for Indonesia and other areas of the Indian Ocean region seven minutes after the earthquake. However, the coastal communities in the Mentawai islands region had very limited time to response due to the fast travelling time of the near field tsunami. Currently, an advanced tsunami early warning system would require 5 minutes to process the information from an earthquake and another additional 15 minutes to issue command to response to the field. Therefore, in the case of the Mentawai islands, the warning would have come too late.

Due to the proximity of potential earthquake sources to Malaysia, the Malaysian public was concerned about the possibility of the earthquake-generated tsunami hitting the Malaysian coast with the ferocity comparable to that of the 2004 event. However, the Mentawai earthquake epicentre is located to the south of Sumatra, and is hence unable to generate tsunamis that might threaten Malaysian coasts. Nevertheless, we still perform simulations for the 25 October 2010 Mentawai tsunami for the purpose of sustaining interests on tsunami simulation and general research. Fig. 6 shows the initial Mentawai tsunami source generated by TUNA based upon the Okada model using the earthquake parameters reported by the United States Geological Survey (USGS), summarized in Table I. The snapshots of the simulated propagation of the Mentawai tsunami are illustrated in Fig. 7.

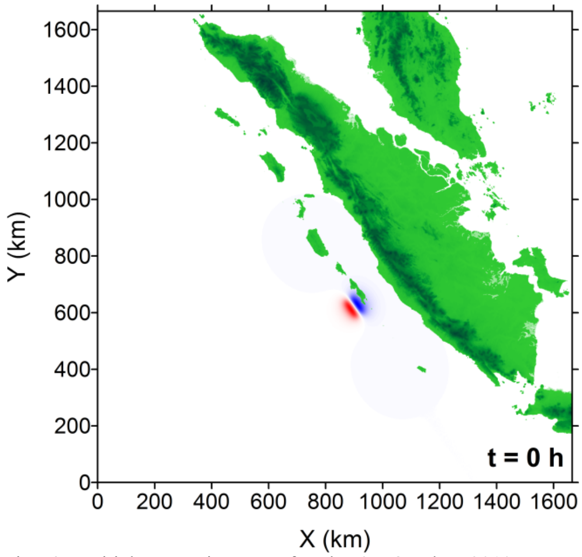


Fig. 6. Initial tsunami source for the 25 October 2010 tsunami in the Mentawai islands region.

TABLE I
INPUT PARAMETERS USED IN THE MENTAWAI TSUNAMI SIMULATION

| Parameter | Unit | Value | Parameter | Unit | Value |
|---|---|---|---|---|---|
| Longitude | °E | 100.11 | Strike | degree | 325 |
| Latitude | °S | 3.48 | Dip | degree | 11.6 |
| Length | km | 66 | Rake | degree | 90 |
| Width | km | 18 | Slip | m | 6 |
| Focal Depth | km | 20 | | | |

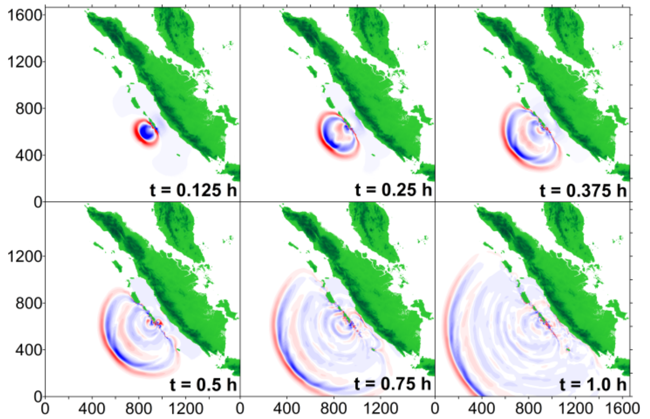


Fig. 7. Snapshots of the propagation of the 25 October 2010 Mentawai islands tsunami.

## IV. Discussion on TUNA Manual

A typical tsunami simulation would begin with site-specific input data preparation that would take considerable time and resources. Hence, the original TUNA simulation model coded in FORTRAN was modified on C# platform [24] in order to simplify input procedure to facilitate learning. This simplicity would facilitate a user to efficiently prepare tsunami simulation input files. This clarity would assist participants in understanding fundamental tsunami propagation characteristics and the various contributing factors that critically affect tsunami behaviour. The simplicity and clarity would then allow initial users to quickly understand and simulate various scenarios to improve their knowledge. Critical tsunami simulation input parameters are defined in Table II, with sample default input window containing relevant parameter values shown in Fig. 8.

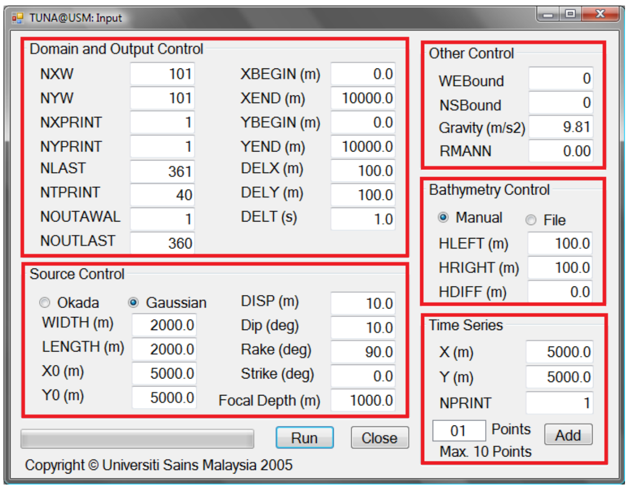


Fig. 8. Default input and control window for TUNA C#.

The explanation contained in Table II and the numerical parameter values given in Fig. 8 can be readily interpreted to refer to a specified simulation scenario chosen. This default scenario provides a basis for meaningful discussion regarding the choice of input in tsunami simulation and the resulting characteristics of tsunami generation and propagation. Various possible scenarios suitable for describing the 2004 Andaman tsunami could be discussed and simulated during the workshops to demonstrate the behaviour of tsunamis. This hands-on numerical experiment and experience would allow participants to quickly learn

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how to perform tsunami simulations for at least some simplified scenarios. It is noted that most participants who were familiar with the 2004 Andaman tsunami were able to develop their own simulation scenarios and create the respective input data files via the C# input window to correctly simulate simplified tsunami scenarios that they had in mind. They then proceeded to plot the simulation output by Surfer and Excel software.

TABLE II
DEFINITION OF INPUT PARAMETERS IN TUNA C#

| Parameter | Unit | Meaning |
|---|---|---|
| *Domain and Output Control* | | |
| NXW | — | Number of computational nodes in x-axis |
| NYW | — | Number of computational nodes in y-axis |
| NXPRINT | — | Printing interval for computational nodes in x-axis |
| NYPRINT | — | Printing interval for computational nodes in y-axis |
| NLAST | — | Number of time iterations to run |
| NTPRINT | — | Printing interval for time iterations |
| NOUTAWAL | — | Number of time iterations to start printing |
| NOUTLAST | — | Number of time iterations to stop printing |
| XBEGIN | meter | Starting point for x-axis |
| XEND | meter | Ending point for x-axis |
| YBEGIN | meter | Starting point for y-axis |
| YEND | meter | Ending point for y-axis |
| DELX | meter | Grid size for x-axis |
| DELY | meter | Grid size for y-axis |
| DELT | second | Computational time step |
| *Source Control* | | |
| WIDTH | meter | Width of fault |
| LENGTH | meter | Length of fault |
| X0 | meter | Latitude of the epicentre of an earthquake |
| Y0 | meter | Longitude of the epicentre of an earthquake |
| DISP | meter | Relative dislocation between foot and hanging blocks on fault plane (Amplitude for the Gaussian hump) |
| Dip | degree | Angle between earth surface and fault plane |
| Rake/Slip | degree | Angle measured counter clockwise from the fault line to the direction of relative motion of hanging block on fault plane |
| Strike | degree | Strike direction of the fault plane, measured from the north to the fault line, with fault plane on the right-hand side |
| Focal Depth | meter | Distance measured vertically from the focus to earth surface |
| *Other Control* | | |
| WEBound | — | Control for west-east boundary condition |
| NSBound | — | Control for north-south boundary condition |
| Gravity | $m/s^2$ | Gravitational acceleration |
| RMANN | $s/m^{1/3}$ | Manning coefficient |
| *Bathymetry Control* | | |
| HLEFT | meter | Depth at western boundary |
| HRIGHT | meter | Depth at eastern boundary |
| HDIFF | m/grid | Depth increment/decrement (meter per grid) |
| *Time Series Control* | | |
| X | meter | X-coordinate of observation point |
| Y | meter | Y-coordinate of observation point |
| NPRINT | — | Printing interval in iteration for time series |

Fig. 9 refers to a tsunami simulation within a square computational domain of 10 km by 10 km (10000 m by 10000 m), with the south-west corner of the domain located at (XBEGIN, YBEGIN) = (0 m , 0 m) and the north-east corner located at (XEND, YEND) = (10000 m, 10000 m). This computational domain can easily be modified to suite a particular simulation scenario. The grid size is DELX = DELY = 100 m, while the time step DELT is 1 s. Both the *x*-axis and *y*-axis are divided into 100 grids each, resulting in a total of NXW = NYW = 101 points in both *x* and *y* directions respectively. The simulation is performed for a total of NLAST = 361 iterations, with output printed every NTPRINT = 40 iterations (or 40 s), beginning with iteration NOUTAWAL = 1. The results are to be printed for every NXPRINT = NYPRINT = 1 point in the *x* and *y* direction respectively. The initial tsunami source is given by the Gaussian formulation, describing a circle centred at the location (X0, Y0) = (5000 m, 5000 m), with a diameter of WIDTH = LENGTH = 2000 m. The domain has a constant depth of HLEFT = HRIGHT = 100 m (HDIFF = 0.0), resulting in a celerity of 31.32 m/s, with gravity of 9.81 $m/s^2$. One (NPRINT = 1) time series of tsunami wave heights at the location (X, Y) = (5000 m, 5000 m) will be printed. However, more time series (NPRINT > 1) can also be printed by request. TUNA C# can accommodate up to several million nodes, which may take several hours to complete simulations.

The simulation results are demonstrated in Fig. 9, showing three snapshots, with the first snapshot at 40 s printed in Fig. 9 (left frame). The tsunami waves continue to propagate symmetrically outwards towards the square boundary and arrive at the boundary at the correct arrival time of 120 s (middle frame of Fig. 9), as correctly indicated by the celerity or travelling speed of 31.32 m/s. The waves subsequently pass through the open boundary with minimal reflection at 240 s (third frame of Fig. 9). It is noted that if the four square boundaries were to consist of solid walls that would reflect incoming waves, then the waves would reflect and would propagate backward from the solid boundary into the square to give rise to interaction of reflected waves inside the square, as shown in Fig. 10. These reflected waves and their interactions produce dangerous situations when tsunamis propagate into a semi-enclosed harbour. It is known that tsunami propagation speed or celerity depends on the depth of the sea through which they propagate. To demonstrate this dependence of speed of tsunami propagation on the ocean depth, we change the sea depth linearly from 100 m to 1000 m, the results of which are depicted in Fig. 11.

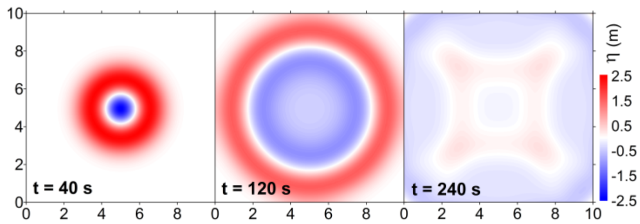

Fig. 9. Snapshots of tsunami propagation in a square domain with open boundaries.

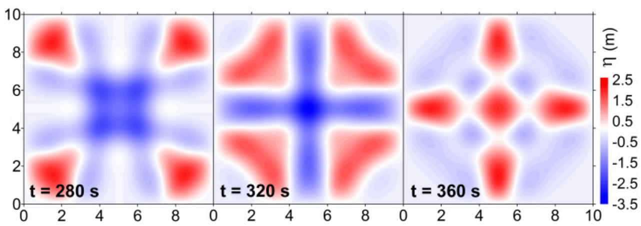

Fig. 10. Snapshots of tsunami propagation in a square domain with solid boundaries.

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Fig. 11 (top row) shows that the wave propagate with the uniform speed of 31.32 m/s, when the depth is a constant 100 m (HLEFT = HRIGHT = 100.0; HDIFF = 0.0). However, when the depth is increased linearly from HRIGHT = 100 m at the eastern boundary to HLEFT = 1000 m at the western boundary (HDIFF = – 9 m per grid), the waves propagate faster in the deeper western half, arriving at the western boundary earlier after 40 s but at the eastern boundary later at 80 s (Fig. 11, middle row). On the other hand when the depth is increased linearly from HLEFT = 100 m at the western (shallower) boundary to HRIGHT = 1000 m at the eastern (deeper) boundary (HDIFF = + 9 m per grid), the propagation speed pattern is reversed. The waves arrive at the deeper eastern boundary earlier after 40 s but arrive at the shallower western boundary later at 80 s (Fig. 11, bottom row).

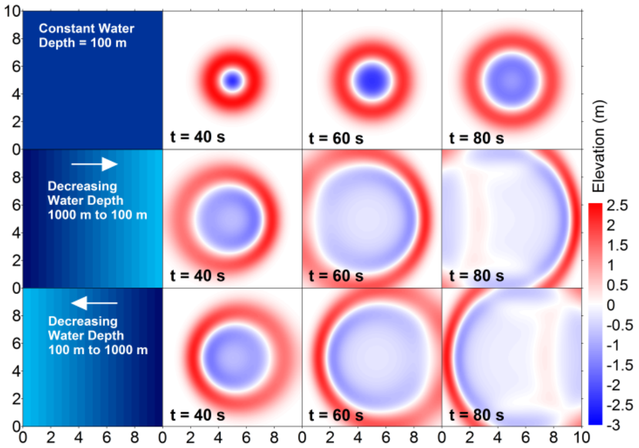


Fig. 11. Snapshots of tsunami propagation in a square domain with constant and linear depth.

## V. Conclusion

This paper presents a brief review of tsunami simulations performed by TUNA for the Andaman Sea and the South China Sea to highlight potential tsunami hazards to the affected coastal regions. To help develop human capacity to conduct tsunami risk simulation, a series of workshops had been conducted in the region. A summary of these workshops and the associated model manual is presented to facilitate tsunami simulation training.

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