Numerical Simulation of Indonesian Tsunami 2004 at Penang Island in Peninsular Malaysia using a Nested Grid Model

Md. Fazlul Karim, Ahmad Izani M Ismail, and Mohammed Ashaque Meah

***Abstract*—**Nested grid modelling techniques are increasingly being recognized as methodologies to aid in multiscale modelling of a variety of atmospheric and oceanic phenomena. A nested grid model with a fine resolution is used to simulate the Indonesian tsunami of 2004 along the coastal belt of Penang Island. The basic primitive model is depth averaged shallow water equations. A fine mesh numerical scheme for the Peninsular Malaysia covering the region between 5º10´ to 5º35´N and 100º to 100º30´E to record fine orographical detail of the region of Penang Island has been nested into a coarse mesh scheme covering the region approximately between 2° N to 14° N and 91° E to 100.5° E which includes the source region of the Indonesian tsunami of 2004. The nesting is accomplished using a scheme Arakawa C staggered grid arrangement. The solutions are obtained for two categories: (a) coarse mesh solution, and (b) nested solution. A nested model is employed in which a coarse grid model is used to supply the open boundary conditions for a finer grid. The major features of the event 2004 along Penang have been successfully simulated by the nested model.

***Keywords*—**Indonesian tsunami 2004, Nested Model, Shallow water equations, Penang Island.

I. INTRODUCTION

Penang Island which lies in the northern part of peninsular Malaysia is vulnerable to the effects of seismic sea waves, or tsunamis, generated along the active subduction zone of Sumatra and that was demonstrated on December 26, 2004. It was reported that 68 people died in Penang state, Malaysia (AFP, [1]) out of which 57 were from Penang Island (Yasin, [14]) and the remaining were from the mainland part of Penang. As the Indian Ocean has several seismic sources, recurrence of the tsunami on the scale of the 2004 event can be anticipated in the future. So, it is essential that tsunamis are studied in detail and prediction models be developed to simulate different aspects of tsunami along the coastal belts of Penang.

Tsunami numerical models have been developed by various investigators. Kowalik et al. [7] developed a spherical polar shallow water model, having very fine mesh resolution, to simulate the Indonesian tsunami of 26 December 2004 throughout the globe between 80^{o} S and 69^{o} N latitudes. A nonlinear polar coordinate shallow water model has been developed by Roy et al. [13] to compute tsunamis due to 2004 Indonesian event along North Sumatra and Penang Island. Karim et al. [5] developed a linear Cartesian coordinate shallow water model for tsunami computation along the west coast of Thailand and Malaysia. Karim et al. [6] also investigated the effect of the different orientations of the source of Indonesian tsunami of 2004 along the coastal belts of Penang Island.

The Malacca strait (Singapore up to Penang Island) is a shallow sea area with an average depth of about 75 m and a maximum depth of 200m. The depth of water in the computational domain which includes the eastern part of the Indian Ocean varies from 5 m to 3000 m (Admiralty bathymetric charts). Since the wave celerity depends on the ocean depth, and the model domain covers both shallow water and the deep sea, large gradient of velocities are expected near the shallow region. When large gradient of a physical quantity within a confined area is expected, the nested grid system is a possible system to enhance the numerical accuracy with the least grid numbers.

Moreover, the coastal belt of the west coast of Peninsular Malaysia has high bending and many off-shore islands. The above coastal belts are also very irregular in shape. Proper incorporation of coastline and island boundaries in a numerical scheme is essential for accurate estimation of water levels due to tsunami. For that purpose a numerical scheme consisting of very fine mesh is required along the coastal belt, whereas this is unnecessary away from the coast. Consideration of very fine mesh over the whole analysis area involves, unnecessarily, more memory and more CPU time in the solution process and invites problem of numerical instability. A nested grid system is especially suitable for incorporation of coastline and island boundaries which require a fine resolution. A nested numerical scheme (inner model

Manuscript received October 9, 2008: Revised version received February 4, 2009.

Md. Fazlul Karim is with *Faculty of Engineering, Universiti Tunku Abdul Rahman, Malaysia*; (e-mail: mdfazlulkk@yahoo.com).

Ahmad Izani M Ismail is with *School of Mathematical Sciences, Universiti Sains Malaysia*, 11800 *Pulau Pinang, Malaysia;* (e-mail: **izani@cs.usm.my**).

Mohammed Ashaque Meah is with Department of Mathematics, Shahjalal University of Science and Technology, Sylhet – 3114, Bangladesh; (e-mail: **mamsust@yahoo.com**).

with fine resolution) within the parent model (outer model with high resolution) can record fine orographical detail in the regions of principal interest. This is particularly important for Penang region.

Most of the past attempts to develop nesting approaches (either one-way or two-way) have been only for storm surge modelling. The most notable contributions are Johns et al. [3], Jones and Davis [4], Roy and Kabir [12]. The grid nesting could be implemented by one of two means: one-way and two-way nesting. In a one-way nested grid model, information from the coarse mesh could enter and affect the fine mesh through the interface between them, while disturbances from the fine mesh do not feed back to the coarse. Because it is simpler and requires less computer time (Koch and McQueen, [8]; Yu and Zhang, [15]), the one-way approach is used in most nested ocean and atmosphere models (e. g. Davis and Flather, [2]; Roy, [11], Monbaliu et al. [9]). In a two-way nested-grid model, however, not only does the coarse grid model affect the fine grid model, but the fine also influences the coarse. Koch and McQueen [8] remarked that the exchange of information between the two grid meshes was more realistic particularly when strong mesoscale disturbances were generated within the fine model.

In this study, in light of bathymetry and the curvilinear nature of Penang Island, a one-way nested numerical scheme is used to compute the effect of Indonesian tsunami of 2004 along the coastal belts of Penang Island.

II. Numerical Model

A. Depth averaged shallow water equations

In Cartesian coordinates, the following governing equations, including the depth-averaged continuity equation and momentum equations were used in the present model. The depth-averaged shallow water equations are

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}\left[(\zeta + h)\,u\right] + \frac{\partial}{\partial y}\left[(\zeta + h)\,v\right] = 0 \qquad (1)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - f\,v = -g\,\frac{\partial \zeta}{\partial x} - \frac{F_x}{\rho\,(\zeta + h)} \qquad (2)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + f\,u = -g\,\frac{\partial \zeta}{\partial y} - \frac{F_y}{\rho\,(\zeta + h)} \qquad (3)$$

where ζ is the sea surface elevation above the undisturbed sea level; h the depth of undisturbed water; u, v the east and north components of the depth-mean current; f the Coriolis parameter; F_x , F_y the components of bottom friction; g the gravity acceleration; C_f the friction coefficient; ρ the water density.

The parameterization of the bottom stress is done by the depth averaged velocity components:

$$F_x = \rho\, C_f\, u\left(u^2 + v^2\right)^{1/2} \text{ and } F_y = \rho\, C_f\, v\left(u^2 + v^2\right)^{1/2} \qquad (4)$$

The origin of the system of coordinates is located on the undisturbed sea surface.

B. Boundary Conditions of parent (outer) model

Other than the west coast of Peninsular Malaysia, the boundaries are considered as straight lines in the open sea. The southern and northern open sea boundaries lie parallel to x-axis and the western open sea boundary lies parallel to y-axis. The radiation boundary conditions for the southern, northern and western open sea boundaries, due to Johns et al. [3], are

$$u - (g/h)^{1/2}\zeta = 0 \quad \text{at the west open boundary; parallel to } y\text{-axis} \qquad (5)$$

$$v + (g/h)^{1/2}\zeta = 0 \quad \text{at the south open boundary; along } x\text{-axis} \qquad (6)$$

$$v - (g/h)^{1/2}\zeta = 0 \quad \text{at the north open boundary; parallel } x\text{-axis} \qquad (7)$$

This type of boundary condition allows the disturbance, generated within the model area, to go out through the open boundary. The coastal belts of the main land and islands are the closed boundaries where the normal components of the current are taken as zero.

III. One-way nesting

There is an economical way to improve the resolution of numerical model by nesting a fine mesh within a coarse mesh, since the nested model can save computer time and memory compared with a model having the same fine resolution throughout the wide model domain (Koch and McQueen, [8]). In a one-way nested grid model, information from the coarse mesh could enter and affect the fine mesh through the interface between them, while disturbances from the fine mesh do not feed back to the coarse. In other words, the coarse model is entirely independent of the fine model. In this paper, a one-way nesting technique was applied in order to improve the accuracy of tsunami modelling.

The domains of the outer coarse mesh (2° N to 14° N latitudes and 91° E to 100.5° E longitudes) and the inner fine mesh ($5^\circ 10' N$ N to $5^\circ 35' N$ and $100^\circ E$ to $100^\circ 30' E$) are shown in Figs. 1 and 2 respectively. The outer model area includes the region where the source of Indonesian tsunami 2004 was located and the inner model area covers the region of Penang Island. The deep ocean was not included in the fine grid and this can save some computer time. The ratio of the coarse grid size, $\left(\frac{1}{30}\right)^{\circ}$ (about 4 km), to the fine grid size, $\left(\frac{1}{120}\right)^{\circ}$ (about 0.8 km), is an integer (5). The time step of the two models is 10 *s* in this study, and this ensures the stability of the numerical scheme. Both the schemes (outer and inner) have the same dynamical equations (1) – (3) with different boundary conditions. The interface conditions, typically including the open boundary conditions of the fine mesh, are of great importance for the one-way nested model in maintaining stability. In this model, the velocity components u, v and water elevation ζ calculated by the $\left(\frac{1}{30}\right)^{\circ}$ resolution outer model (extending to the deep water offshore) are used as the boundary values of $\left(\frac{1}{120}\right)^{\circ}$ resolution coupled at inner models in the shallow estuary. The high resolution model depends therefore on the dynamics of the coarse resolution model but the coarse resolution model is not influenced by the fine resolution model. This has the advantage that the models can be run successively starting with the coarse resolution model. The coupling of the coarser and finer grid model is done according to Johns et al. [3], who maintained the interaction between the parent (outer) and nested models is one way. This implies that the outer model drives the nested (inner) model but the response in the nested model does not affect that in the outer model.

IV. Initial condition (Tsunami source generation in outer model)

The generation mechanism of the 26 December 2004 tsunami was mainly due to a static sea floor uplift caused by an abrupt slip at the India/Burma plate interface. A detailed description of the estimation of the extent of the earthquake rapture as well as the maximum uplift and subsidence of the seabed is given in Kowalik et al. [7] and this estimation is based on Okada [10]. From the deformation contour, it is seen that the estimated source zone is between 92° E to 97°E and 3°N to 10°N, elongated along the fault which is aligned from south-east to north-west, with a maximum uplift of 507 cm at the west and maximum subsidence of 474 cm at the east (Fig. 4 of Kowalik et al. [7]. The uplift to subsidence is approximately from west to east. Following Kowalik et al. [7], the disturbance in the form of rise and fall of sea surface is assigned as the initial condition in the outer model with a maximum rise of 5 m to maximum fall of 4.75 m. In all other regions the initial sea surface elevations are taken as zero. The initial x and y components of velocity are also taken as zero throughout the model area.

V. Results and Discussion

A. *Results obtained from Outer Model*

The governing equations (1)-(3) along with the boundary conditions (5)-(7) which are described in section 2 are solved by using a finite difference scheme. Wave propagation of the source is computed and water levels along the coastal belts of the Penang Island are estimated.

A.I. Propagation of Tsunami towards the Penang Island

Results from the numerical simulation of the propagation of tsunami towards the west coast of Peninsular Malaysia are shown in Figures 3 - 6. The disturbance pattern of the sea surface is presented at four different instants of time.
At 1 h after the generation of the initial tsunami wave at the source, the sea surface disturbance is found to proceed towards Phuket in Southern Thailand with a trough at the front followed by a crest (Fig. 3) and it hits the Phuket coast at 1.5 h after the generation (Fig. 4). The wave is then propagating towards the Penang Island after flooding the Phuket region (Fig. 4). In 2.5 h the disturbance propagates further towards Penang Island (Fig. 5) and finally at 4 h the tsunami surge is hitting the north and west coasts of Penang Island (Fig. 6).

A.II. Arrival Time of Tsunami

The arrival time plays an important role in prediction and early warning systems of tsunami. In Fig 7, the tsunami arrival time is shown in the form of contour plot in time (minutes). It is seen that after initiating the source, the disturbance propagates gradually towards the coast of Phuket Island in Southern Thailand. Then, the disturbance continues propagating towards Penang Island and reaches the north-west coast. The arrival times of tsunami at Penang Island are approximately 220 minutes. The propagation slows down at Malacca Straits because of shallow water along this strait which is consistent with the fact that a long wave speed reduces in shallow water. Simulation result shows earlier arrival time than the observation available in USGS website. Past studies (Roy et al. [13], Karim et al. [6] without nesting) also show the similar results for arrival time.

B. *Results obtained from Inner Nested Model*

B.I. Computed Time Series of Water Levels along the Penang Island

The computed water levels at four locations of the coastal belt of Penang Island are stored at an interval of 30 seconds.

Figure 8 shows the results at four locations at the north, west and south coasts of Penang Island in Malaysia. At Batu Ferringi (north coast) the maximum elevation is approximately 3.6 m (Fig. 8a). At approximately 3 hrs after the generation of tsunami at the source the water level starts decreasing as the response to the tsunami source and reaches a minimum level of –2.6 m. Then the water level increases continuously to reach a level of 2.2 m (1st crest) at 3 hrs 40 min before going down again. The water level oscillates and this oscillation continues for several hours. At the location Tanjung Tokong (north-west coast) the maximum elevation is approximately 3.2 m (Fig. 8b). Near Pasir Panjang (south-west coast) the maximum elevation is found to be 3.0 m (Fig. 8c) and at the south coast the same is 2.1 m (Fig. 8d).). Thus the computed results show that the north-west coast of Penang Island is vulnerable for stronger tsunami hazard.

B.II. Estimation of Water Level along the coasts and Corresponding Time

Figure 9 depicts the maximum water level contours, along the coast of Penang Island; the surge amplitude is increasing along the coast from south to north. The maximum water level at Penang Island is from 2 m to 4.5 m. The surge amplitude is increasing very fast near the shoreline everywhere. The computed water levels indicate that the north and west coasts of Penang Island is vulnerable for stronger surges.

The numerical simulation computes the travel time of tsunami at every grid point as the time of attaining +0.1 m sea level rise and the results are presented in Fig. 10 in the form of time contours. It is seen that the arrival time of tsunami surge along north coast is between 230 and 240 min and the arrival time of surge along the south coast is between 250 and 260 min. The USGS website [(http://staff.aist.go.jp/kenji.satake/Sumatra-E.html) (Tsunami travel time in hours for the entire Indian Ocean)] confirms the fact that the arrival time of tsunami at Penang is between 4 hr and 4 hr 30 min. Hence the computed travel times are in good agreement with those of USGS observations.

VI. Conclusion

A one-way nested coupled tsunami computation model was developed in this study and applied to compute the Indonesian tsunami of 2004 along the coastal belts of Penang Island. The one-way nested technique, which makes it possible for more reasonable values for the open boundaries to be supplied from the coarse mesh to the fine mesh model, was successfully applied in this model. It was observed that there was a slight improvement in agreement with observed data using the one-way nesting technique than that of previous studies (without nesting).

Acknowledgment

This research is supported by the research grant by the Government of Malaysia and the authors acknowledge the support.

References

[1] AFP, (2005), Death toll in Asian Tsunami Disaster. http://story.news.yahoo.com/news?tmpl=story2&u=/afp/20050305/wl_asia_afp/asiaquaketoll

[2] A. M.,Davies., R. A. Flather, "Application of numerical models of the North West European continental shelf and the North Sea to the computation of the Storm Surges of November to December 1973", Deutsche Hydrographische Zeitschrift Erganzungsheft Reihe A, 1987, 14, 72pp.

[3] B. Johns., A. D. Rao., S. K. Dube., P. C. Sinha, " Numerical modelling of tide-surge interaction in the Bay of Bengal", Phil. Trans. Roy. Soc. London, 1985, A 313, 507 – 535.

[4] J. E. Jones., A. M. Davis," Storm Surge computations for the Irish Sea using a three dimensional numerical model including wave-current interaction, Continental Shelf Research", 1998, 18, 201-251.

[5] M.F. Karim., G. D. Roy., A. I. M. Ismail., M. A. Meah, "A linear Cartesian coordinate shallow water model for tsunami computation along the west coast of Thailand and Malaysia", *Int. J. of Ecology & Development*, 2006, 4(S06): 1 – 14.

[6] M. F. Karim., G. D. Roy., A. I. M. Ismail, "An Investigation on the Effect of Different Orientation of a Tsunami Source along the Coastal Belt of Penang Island: A Case Study of the Indonesian Tsunami 2004", *Far East J. of Ocean Research*, 2007, 1 (1), 33-47.

[7] Z. Kowalik., W. Knight., P. M. Whitmore, " Numerical Modeling of the Global Tsunami: Indonesian Tsunami of 26 December 2004. Sc. Tsunami Hazards", 2005, 23(1), 40 – 56.

[8] S. E. Koch., J. T. McQueen," A survey of nested grid techniques and their potential for use within the MASS weather prediction model, NASA Technical Memorandum 87808", National Aeronautics and Space Administration, 1987, USA.

[9] J. Monbaliu., R. Padilla-Hernandez., J. C. Hargreaves., A. H.C. Carretero., W. Luo., M. Sclavo., H. Gunther, " The spectral wave model, WAM, adapted for applications with high spatial resolution", Coastal Engineering, 2000, 41, 41 – 62.

[10] Y. Okada, "Surface Deformation due to Shear and Tensile Faults in a Half Space", *Bull, Seism. Soc. Am.*, 1985, 75, 1135 – 1154.

[11] G. D. Roy," Estimation of expected maximum possible water level along the Meghna estuary using a tide and surge interaction model", *Environment International*, 1995, 21(5), 671-677.

[12] G. D. Roy., A.B.M.H. Kabir, "Use of a nested numerical scheme in a shallow water model for the coast of Bangladesh", BRAC University Journal, Bangladesh, 2004, 1 (1).

[13] G. D. Roy., M. F. Karim., A. I. M. Ismail, "A Non-Linear Polar Coordinate Shallow Water Model for Tsunami Computation along North Sumatra and Penang Island", *Continental Shelf Research*, 2007, 27, 245–257.

[14] Z. Yasin, "The Tsunami Timeline. The School of Biological Science Bulletin, University Sains Malaysia", 2005, Vol VIII, 26.

[15] F. J. Yu and Z. H. Zhang, "Implementation and application of a nested numerical storm surge forecast model in the East China Sea", Acta Oceanologica Sinica, 2002, 21 (1), 19-31.

Figure 1: Outer model domain including west coast of Thailand, Peninsular Malaysia and source zone west of North Sumatra.

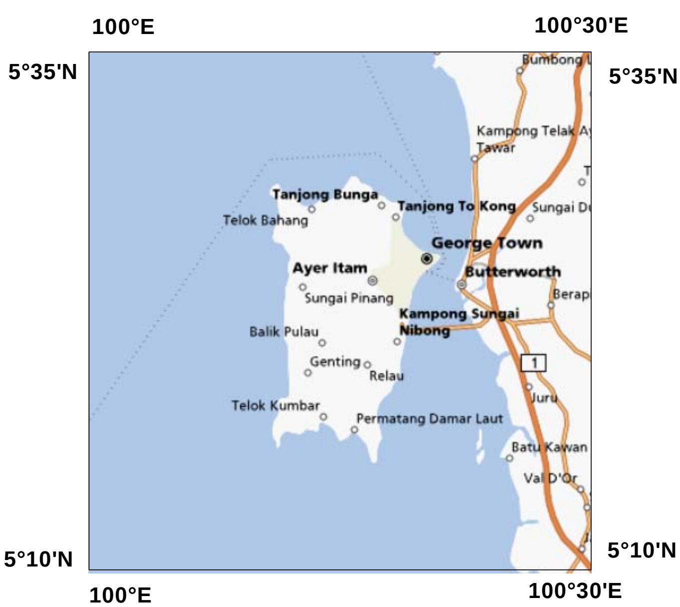

Figure 2: Inner model domain.

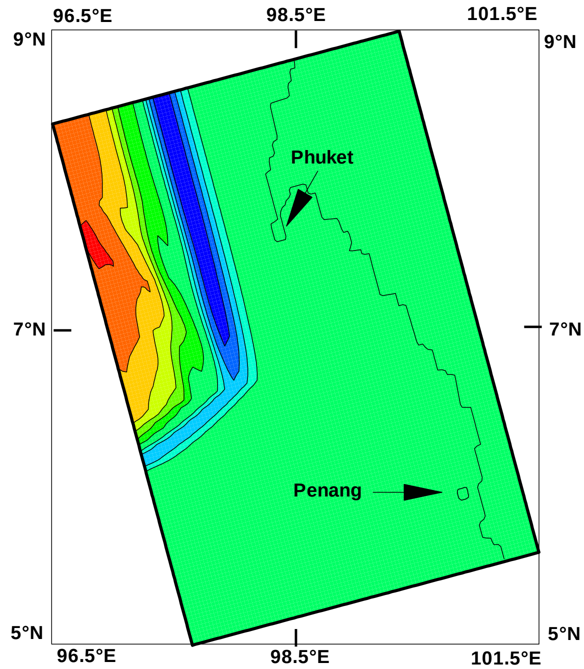

Figure 3: Propagation of tsunami at 1.0 hr.

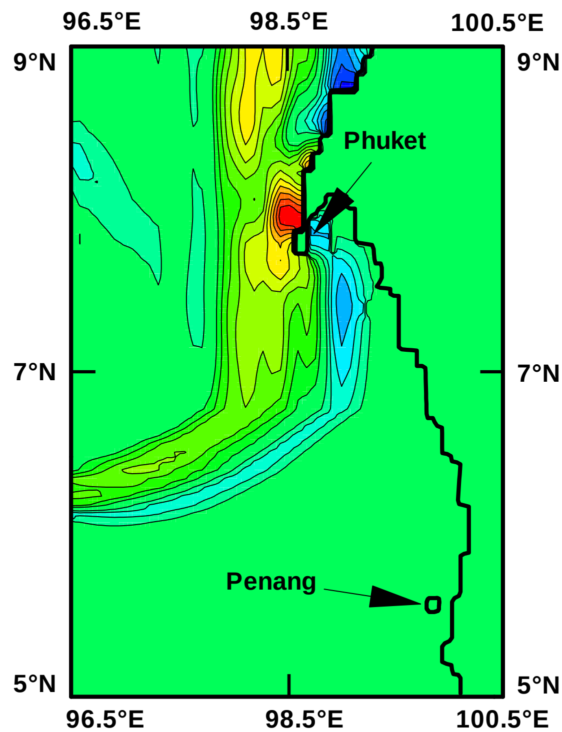

Figure 4: Propagation of tsunami at 1.5 hr.

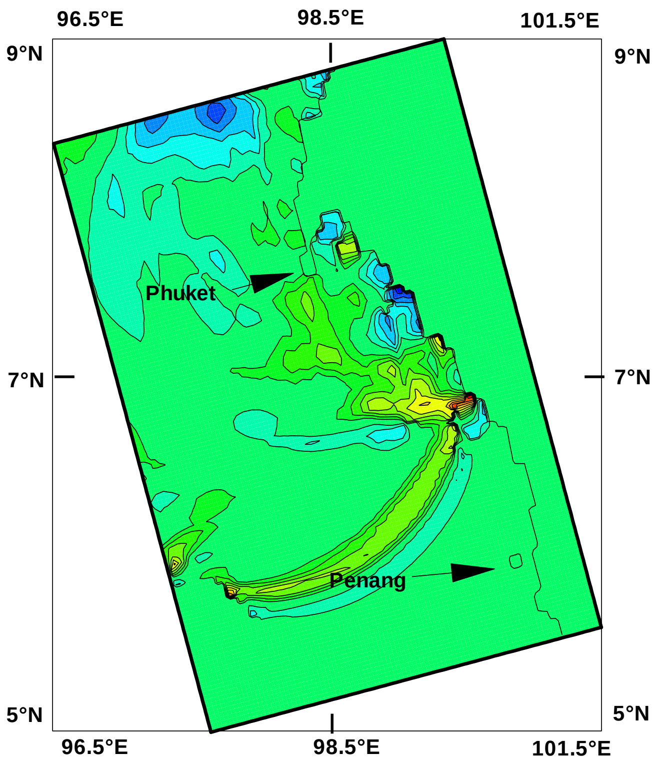

Figure 5: Propagation of tsunami at 2.5 hr.

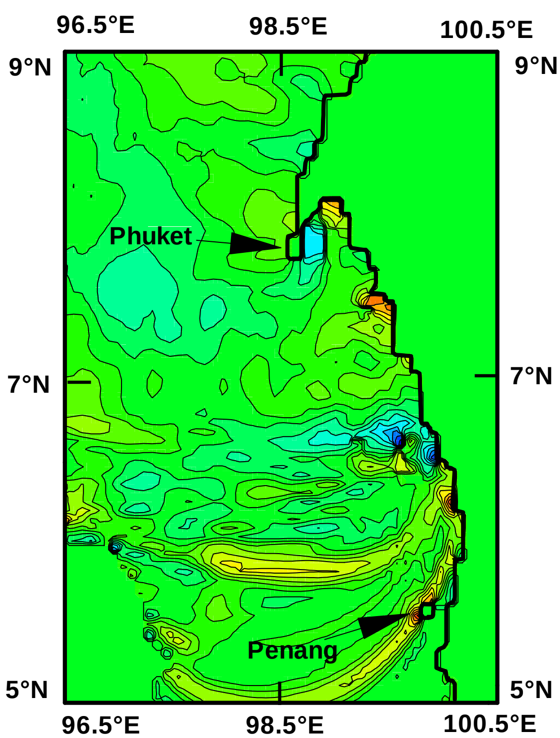

Figure 6: Propagation of tsunami at 4 hr.

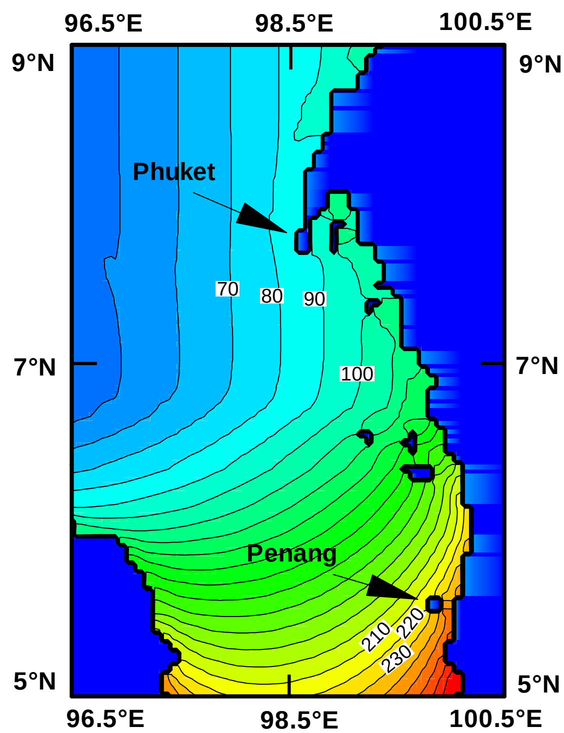

Figure 7: Contour showing tsunami propagation time in minutes; sea level rise of 0.1 m is considered as the arrival of tsunami.

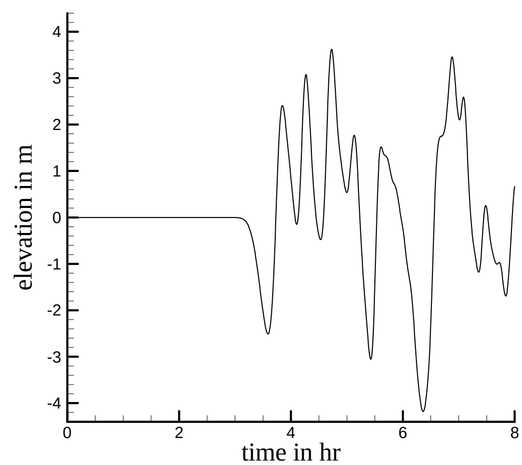

Figure 8a: Time series of computed elevation at coastal location of Batu Ferringhi (North-west).

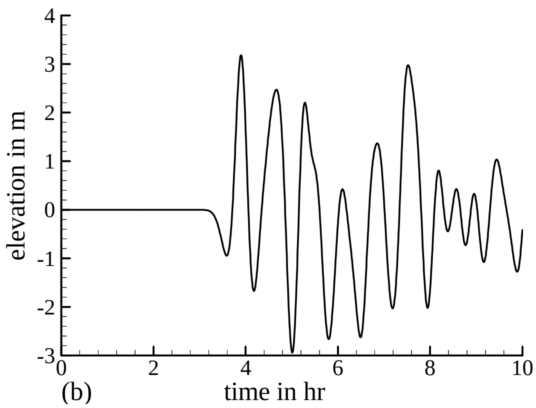

Figure 8b: Time series of computed elevation at coastal location of North-west Penang.

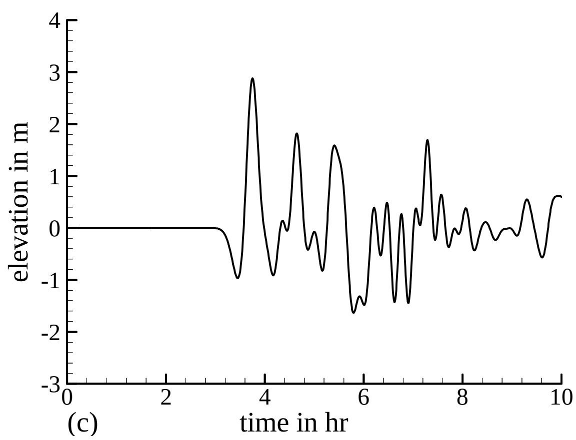

Figure 8c: Time series of computed elevation at coastal location of South-west Penang.

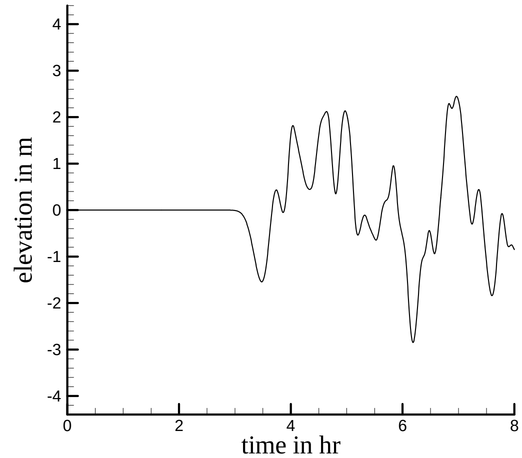

Figure 8d: Time series of computed elevation at coastal location of South Penang.

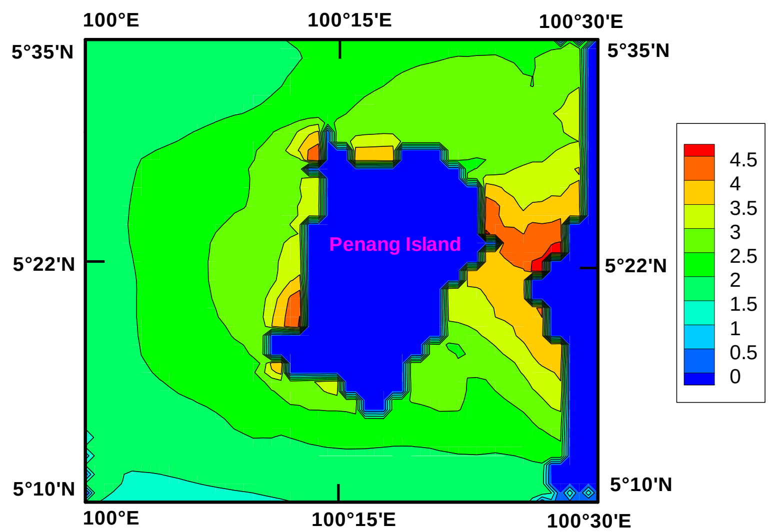

Figure 9: Contour of maximum water levels around the Penang Island associated with the Indonesian tsunami 2004.

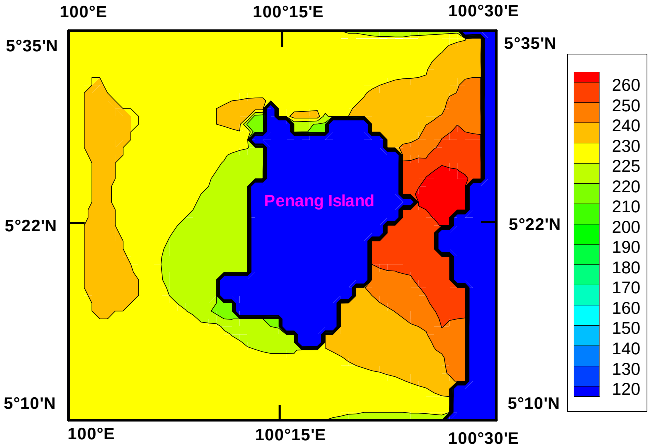

Figure 10: Contour of times, in minutes, of attaining maximum water levels around the Penang Island associated with the Indonesian tsunami 2004.