A one-way nested tsunami computation model for the Penang Island in Peninsular Malaysia

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Abstract: A one-way nested tsunami computation model is developed and applied to compute the response of the 2004 Indonesian tsunami along the coastal belts of Penang Island in Peninsular Malaysia. In this study, a one-way nested finite difference scheme is used to solve the depth averaged shallow water equations in Cartesian coordinates. A fine mesh numerical scheme (inner scheme) for the west coast of Malaysia covering 5º10´-5º35´N and 100º-100º30´E has been nested into a coarse mesh scheme (outer scheme) enclosing 2º-14ºN and 90º-100º30´E. The fine mesh scheme incorporates the Penang Island more accurately as the grid size is considered small. In a one-way nested grid model, information (velocity components and sea surface elevation) from the coarse mesh scheme could enter and affect the fine mesh scheme through the interface between them in each time step of the solution process, while disturbances from the fine mesh do not feed back to the coarse one. The outer scheme is thus running completely independent in each time step of the solution process. A simulation experiment shows that the performance of the inner scheme of the one-way nested model is superior in accuracy compared to that of outer scheme. Different aspects of tsunami along the coastal belts of Penang Island have been computed through outer and inner schemes and the results are found to be satisfactory.

Key words: Coupled tsunami model, Tsunami, Penang Island, Indonesian Tsunami 2004.

1. Introduction

Penang Island in the northern part of Peninsular Malaysia is vulnerable to seismic sea waves, or tsunamis, generated along the active subduction zone of Sumatra and that was demonstrated on 26 December 2004. It was reported that 68 people died in Penang state of Malaysia (AFP, 2005), out of which 57 were from Penang Island (Yasin, 2005) and the remaining were from the mainland land of Penang. As the Indian Ocean has several seismic sources, recurrence of tsunamis on the scale of 2004 event can be anticipated in 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 Island.

Tsunami models have been developed by various investigators after occurrence of 2004 Indonesian event. Kowalik et al. (2005) developed a spherical polar shallow water model, with a very fine mesh resolution, to simulate the 2004 Indonesian tsunami throughout the globe between 80ºS and 69ºN latitudes. A nonlinear polar coordinate shallow water model has been developed by Roy et al. (2007) to compute tsunamis due to 2004 Indonesian event along North Sumatra and Penang Island. Karim et al. (2006) developed a linear Cartesian coordinate shallow water model for tsunami computation along the west coast of Thailand and Malaysia. Karim et al. (2007) also investigated the effect of the different orientations of the source of 2004 Indonesian tsunami along the coastal belts of Penang Island.

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. (1985), Roy et al. (1995), Jones and Davis (1998), Roy and Kabir (2004). The grid nesting could be implemented by one-way or two-way. In a one-way nested grid model, information (velocity components and sea surface elevation) 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 one. Because it is simpler and requires less computer time (Koch and McQueen, 1987; Yu and Zhang, 2002), the one-way approach is used in most nested ocean and atmosphere models (e.g. Davis and Flather, 1987, Johns et al. 1985, Roy 1995, Monbaliu et al. 2000). In a two-way nested-grid model, however, not only does the coarse grid scheme affect the fine scheme, but also the fine one influences the coarse one. Koch and McQueen (1987) remarked that the exchange of information between the two meshes was more realistic particularly when strong mesoscale disturbances were generated within the fine model.

The west coast of Peninsular Malaysia has high bending, very irregular in shape and many off-shore islands. 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 scheme with fine resolution) within the parent model (outer scheme with coarse resolution) can record fine orographical detail in the regions of principal interest and this is particularly important for Penang region.

The Malacca strait (Singapore to Penang) is a shallow sea with an average depth of about 75 m and a maximum depth of 200m. On the other hand, the whole computational domain of the present study (2º-14º N and 90º-100º30´E.) includes eastern part of the Indian Ocean and the depth varies from 5 m to 3000 m. Since the wave celerity depends on ocean depth, and the model domain covers both shallow water and deep sea, large gradient of velocities are expected near shallow regions. When large gradient of a physical quantity within a confined area is expected, the nested grid system is a possible method to enhance the numerical accuracy with the least grid numbers.

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

2. Numerical Model

2.1. Depth averaged shallow water equations

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

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x} [(\zeta + h)u] + \frac{\partial}{\partial y} [(\zeta + h)v] = 0 \tag{1}
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - f v = -g \frac{\partial \zeta}{\partial x} - \frac{F_x}{\rho (\zeta + h)} \tag{2}
\]

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + f u = -g \frac{\partial \zeta}{\partial y} - \frac{F_y}{\rho (\zeta + h)} \tag{3}
\]

where \(\zeta\) is the sea surface elevation above the undisturbed sea level; \(h\) the depth of undisturbed water; \(u, v\) the \(x\)- and \(y\)- 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; \(\rho\) the water density.

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

\[
F_x = \rho C_f u \left( u^2 + v^2 \right)^{1/2} \quad \text{and} \quad F_y = \rho C_f v \left( u^2 + v^2 \right)^{1/2} \tag{4}
\]

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

2.2. 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. (1981), are

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

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

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

3. One-way nesting

There is an economical way to improve the resolution of a 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, 1987). 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 one. In other words, the coarse scheme is entirely independent of the fine mesh scheme.

The domains of the outer coarse mesh ($2^\circ$ N - $14^\circ$N and $91^\circ$E -100.5$^\circ$E) and the inner fine mesh ($510^\prime$N - $535^\prime$N and $100^\circ$E -100$30^\prime$E ) are shown in Figs. 1 and 2 respectively. The outer scheme area includes the region where the source of 2004 Indonesian tsunami is located and the inner scheme area covers the Penang Island. Since the deep ocean has not been included in the fine grid scheme area the time step can be considerably large and this can save some computer time. The ratio of the coarse grid size, ($130$) (about 4 km), to the fine grid size, ($1/120$) (about 0.8 km), is an integer (5). The time step for each scheme is taken as 10 s, 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. For the outer scheme the boundary conditions (5) – (7) are used in each time step of the solution process. 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, each interface is a matching of an open boundary grid line of the inner scheme with the appropriate grid line of the outer scheme. The velocity components $u$, $v$ and elevation $\zeta$ computed by ($130$) resolution along the matching grid line of outer scheme in each time step are used as the boundary values of ($1/120$) resolution along the matching boundary grid line of the inner scheme. The high resolution inner scheme is thus depends on the dynamics of the coarse outer scheme but the coarse one is not influenced by the fine resolution scheme. This has the advantage that the models can be run successively starting with the coarse resolution scheme. The coupling of the coarser and finer schemes is done according to Johns et al. (1985), who maintained the one way interaction between the parent (outer) and nested schemes of the model. This implies that the outer scheme drives the nested (inner) scheme but the response in the nested scheme does not affect the outer scheme of the model.

4. Initial condition (Tsunami source generation in outer scheme)

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. (2005) and this estimation is based on Okada (1985). 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. (2005). The uplift to subsidence is approximately from west to east. Following Kowalik et al. (2005), 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.

5. Results and Discussion

5.1 Results obtained from Outer Scheme

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

5.1.1 Propagation of Tsunami towards Penang Island

Results from the numerical simulation of propagation of tsunami towards the west coast of Peninsular Malaysia are shown in Figs. 3 and 4 in the form of contour of sea surface elevation. The disturbance pattern of the sea surface is presented at two different instants of time. At 1.5 hr after the generation of the initial tsunami wave at the source, the sea surface disturbance is found to be proceeding towards Penang island in Peninsular Malaysia after flooding the Phuket region (Fig. 3) and finally at 4 hr the tsunami surge is hitting the north and west coasts of Penang Island (Fig. 4).

5.1.2 Arrival Time of Tsunami

The arrival time plays an important role in prediction and early warning systems of tsunami. In Fig 5, the tsunami arrival time is shown in the form of contour plot in minutes; time of +0.1 m sea level rise at each grid point is considered as the arrival tsunami at that point. 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 at approximately 220 minutes. The propagation slows down at Malacca Straits because of very shallow water along this strait and this is consistent with the fact that a long wave speed reduces in shallow water. Computed result shows earlier arrival of tsunami than that of observation available in USGS website. Past studies (Roy et al. 2007, Karim et al. 2007 without nesting) also show the similar results on arrival time.

5.2 Results obtained from Inner Nested Scheme

5.2.1 Computed Time Series of Water Levels along the Penang Island

The computed water levels at two locations of the coastal belt of Penang Island are stored at an interval of 30 seconds. Figure 6 shows the time series of water levels at Batu Ferringhi (north-west coast) and at Pasir Panjang (south coast) of Penang Island. At Batu Ferringhi, the maximum elevation is approximately 3.4 m (Fig. 6a). The water level shows oscillatory behavior and the oscillation continues for several hours. At Pasir Panjang, the result shows the same pattern as that of Batu Ferringhi but with different maximum elevation of 2.2 m (Fig. 6b). Thus the computed results show that the north-west Coast of Penang Island is vulnerable for stronger tsunami hazard.

5.2.2 Estimation of arrival Time of Tsunami

The numerical simulation of the travel time of tsunami at every grid point, as the time of attaining +0.1 m sea level rise, is presented in Fig. 7 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 same 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.

6. Conclusions

In this study a one-way nested coupled tsunami computation model is developed and applied to compute the 2004 Indonesian tsunami along the coastal belts of Penang Island. In the one-way nested technique, it has been possible for more reasonable values for the open boundaries of the inner scheme to be supplied from the coarse mesh scheme. It is observed that there is a slight improvement in agreement with observed data using the one-way nesting technique than that of previous studies without nesting.

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References

[1] AFP, (2005), Death toll in Asian Tsunami Disaster


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

Figure 2: Inner model domain.

epicenter
Figure 3: Propagation of tsunami at 1.5 hr.

Figure 4: Propagation of tsunami at 4 hr.

Figure 5: Contour showing tsunami propagation time in minutes; sea level rise of 0.1 m is considered as the arrival of tsunami.
Figure 6: Time series of computed elevation at two coastal locations of Penang Island

(a) Batu Ferringhi (North-west)  (b) South Penang

Figure 7: Contour of times, in minutes, of attaining maximum water levels around the Penang Island associated with the Indonesian tsunami 2004