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ESTIMATION OF EXPECTED MAXIMUM WATER LEVEL DUE TO TIDE AND TSUNAMI INTERACTION ALONG THE COASTAL BELTS OF PENANG ISLAND IN PENINSULAR MALAYSIA

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ABSTRACT

In this paper, an estimate of the expected maximum water levels associated with tide and tsunami interaction is computed along the coastal belts of Penang Island in Peninsular Malaysia. For this purpose, a nonlinear Polar coordinate shallow water model of the Indonesian tsunami of 2004 by Roy et al. (2007b) is used. Appropriate tidal condition is generated in the domain by applying tidal forcing through the western open sea boundary. For studying tide and tsunami interaction, the 2004 Indonesian tsunami is introduced in the previously generated tidal oscillation. The expected maximum possible water level along the coastal belts of Penang Island is estimated based on the interaction of tide and tsunami for different tidal conditions (high and low tidal periods). It is seen that the surge level is very sensitive towards the coastal belts due to interaction during high tide. The west coast of Penang Island is found to be vulnerable for stronger surge due to interaction. The influence of tidal wave on the tsunami wave height towards Penang Island is also investigated. The tide was found to have a significant effect in tsunami enhancement in the coastal regions.

Key words: Tide, Surge, Penang Island, Indonesian Tsunami 2004.

1. INTRODUCTION

The coastal environment is diverse, with astronomical tides, wind, waves and currents; all contributing to the forces experienced by coastal features. An example of a devastating natural calamity is the event that occurred in the Indian Ocean on 26 December 2004. An important phenomenon in applied coastal oceanography is the interaction of high astronomical tides and tsunami. Tides are the rising and falling of Earth's ocean surface caused by the tidal forces of the Moon, the Sun and other planets acting on the oceans. The interaction of tides and tsunami leads to significant high water levels, thus increasing the risk of coastal flooding, shoreline erosion and damage of urban drainage systems. Furthermore, an increase in the mean water level together with large tsunamis may produce severe damages to coastal structures, which are usually designed without taking into account an abnormal rise of in the sea level.

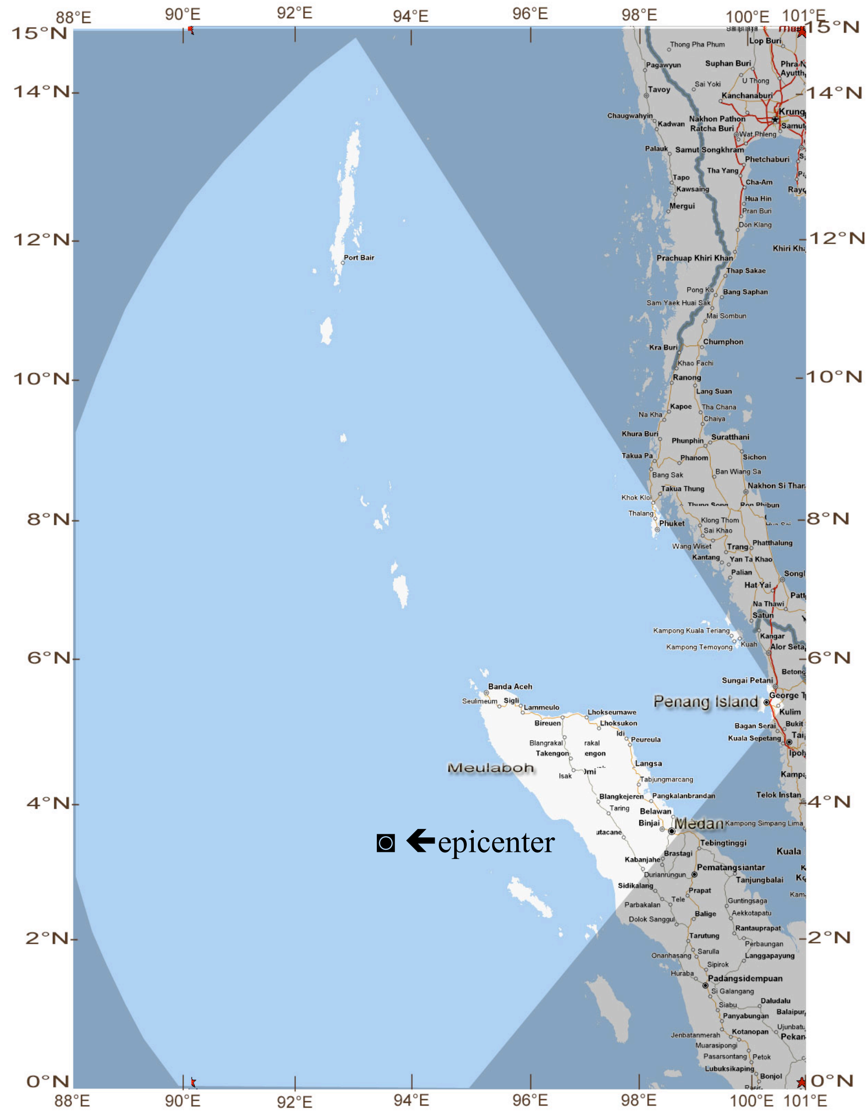

Figure 1: Map of the model domain including North Sumatra and Penang Island

The Malacca strait (Singapore up to Penang Island) is a large tidal range (difference between high and low tide) area. Among the tidal constituents *M*2 and *S*2, due to attractions of the moon and the sun respectively, are predominant in the region. Since the astronomical tidal phenomenon is a continuous process in the sea, tsunamis always interact with the astronomical tide and so the pure tidal oscillation in the whole basin should be considered as the initial dynamical condition for the tide-tsunami interaction phenomenon. The interaction with tide is generally nonlinear and the nonlinear effect is prominent in the very shallow regions; for example near a island or coastal belt. So in order to compute accurately the tsunami in a particular coastal region it is necessary that the interaction of tide and tsunami should be carried out.

Many studies concerning tide, surge due to tropical storms and their interaction can be found in the literature (e.g. Flather 1976, 1981; Flather and Davies, 1976; Heaps and Jones, 1981; Nihoul, 1977, 1982; Johns et al. 1985, Roy 1995). Considerable studies have also been done for the computation of Indonesian tsunami of 2004. Examples include Kowalik et al. (2005), Kowalik and Proshutinsky (2006), Roy and Izani (2006), Roy et al. (2007 a, b) and Karim et al. (2007). Kowalik and Proshutinsky (2006) investigated the dynamics defining tsunami enhancement in the coastal regions and related to interaction with tides. In their study, two simple cases of tide/tsunami interactions along a narrow and wide shelf have been investigated to define importance the nonlinear interactions. However, the tidal effect on tsunami propagation has not been fully investigated.

The present paper addresses this important aspect in applied coastal oceanography: the nonlinear interaction of high astronomical tides and tsunami which lead to higher water levels. The initial tsunami wave is generated in the deep ocean with the strength that of Indonesian tsunami 2004 which occurred at approximately 160 km west of North Sumatra (Fig 1). The purpose of the paper is to estimate the expected maximum possible water level due to tide and tsunami interaction along the coastal belts of Penang Island in Peninsular Malaysia. This information might be needed, for example, to build the base of a tsunami and a storm surge shelter at a particular region along a coastal belt.

2. THE MATHEMATICAL MODEL

2.1. *Shallow water equations*

We introduce the vertically integrated shallow-water equations in Polar form, which are, in standard notation (Roy et al. 2007b):

$$\frac{\partial \zeta}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left[r(\zeta + h)v_r\right] + \frac{1}{r}\frac{\partial}{\partial \theta}\left[(\zeta + h)v_\theta\right] = 0 \tag{1}$$

$$\frac{\partial v_r}{\partial t} + v_r\frac{\partial v_r}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta} - f v_\theta = -g\frac{\partial \zeta}{\partial r} - \frac{C_f\, v_r\,(v_r^2 + v_\theta^2)^{1/2}}{\zeta + h} \tag{2}$$

$$\frac{\partial v_\theta}{\partial t} + v_r\frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta} + f v_r = -\frac{g}{r}\frac{\partial \zeta}{\partial \theta} - \frac{C_f\, v_\theta\,(v_r^2 + v_\theta^2)^{1/2}}{\zeta + h} \tag{3}$$

where v_r = radial component of velocity of the sea water, v_θ = tangential component of velocity of the sea water, f = Coriolis parameter = $2\,\Omega\sin\varphi$, Ω = angular speed of the earth , φ = latitude of the location, g = acceleration due to gravity, ρ = the sea water density, C_f = the coefficient of friction.

2.2. ***Boundary conditions***

For a closed boundary the normal component of velocity is considered as zero. The radiation type of boundary conditions are used for open boundaries which allow the disturbance created within the analysis area to go out of the area. The analysis area is bounded by the radial lines $\theta = 0°$, $\theta = \Theta = 110°$ through O and the circular arc $r = R$ (Fig. 1). Following Roy et al. (1999) the northern and southern open sea boundary conditions are respectively given by

$$v_\theta + \sqrt{(g/h)}\ \zeta = 0 \quad \text{along } \theta = 0 \tag{4}$$

$$v_\theta - \sqrt{(g/h)}\ \zeta = 0 \quad \text{along } \theta = \Theta \tag{5}$$

For generating tide in the basin at the circular open sea west boundary, the condition is taken as

$$v_r - \sqrt{(g/h)}\ \zeta = -2\left(\frac{g}{h}\right)^{\frac{1}{2}} a \sin\left\{(2\pi t)/T + \phi\right\} \quad \text{along } r = R \tag{6}$$

where a is the amplitude, T is the tidal period, φ is the initial phase.

2.3. ***Transformation for uneven resolution along radial direction***

The polar coordinate system automatically ensures finer resolution along tangential direction near the region of the pole. By setting the Pole suitably at the location where fine resolution is required, a uniform grid of size $\Delta\theta$ is generated in the tangential direction by a set of radial lines through the Pole. The arc distance between any two successive radial lines decreases towards the Pole and increases away from the pole. Thus uneven resolution is achieved in the tangential direction although uniform grid size $\Delta\theta$ is used.

To achieve uneven resolution along radial direction, fine to coarse in the positive radial direction, according to Haque et al. (2005), the following transformation is used:

$$\eta = c \ln\left(1 + \frac{r}{r_0}\right) \tag{8}$$

where r_0 is a constant of the order of total radial distance and c is a scale factor. From this transformation we obtain a relationship between Δr and $\Delta\eta$ which is as follows:

$$\Delta r = \frac{r + r_0}{c}\Delta\eta \tag{9}$$

This relation shows that, keeping the value of $\Delta\eta$ as constant, we can generate a variable Δr. For a constant value of $\Delta\eta$, Δr will increase with increase of r, so that we obtain uneven resolution (fine to coarse) in the radial direction in the physical domain while in computational domain the resolution remains uniform. The boundary conditions will remain unchanged under the transformation.

3. GRID GENERATION AND NUMERICAL SCHEME

3.1. *Grid generation*

In the physical domain the grid system is generated through the intersection of a set of straight lines given by θ = *constant* through the Pole *O* (5° 22.5′ N, 100° 30′ E) and concentric circles, with centre at *O*, given by r = *constant*, where the total number of grids are 778×307. The angle, $\Delta\theta$, between any two consecutive straight grid lines through *O* is constant; whereas the distance between any two consecutive circular grid lines, Δr, increases in the positive radial direction. After the transformation (8), both $\Delta\theta$ and $\Delta\eta$ become uniform where $\Delta\theta$ is set to be (110/306)° and $\Delta\eta$ is set to be 1/777.

3.2. *Numerical scheme and implementation of the tsunami source*

The governing equations and the boundary conditions are discretized by finite-difference (forward in time and central in space) and are solved by a conditionally stable semi-implicit method using a staggered grid system, similar to the Arakawa C, as described in Roy et al. (1999). The time step is taken as 10 seconds that ensures the CFL stability criterion of the numerical scheme. The values of the friction coefficient is taken as uniform (C_f = 0.0033) throughout the physical domain. The depth data used in this study are collected from the Admiralty bathymetric charts.

The generation mechanism of the 26 December 2004 tsunami was mainly due a static sea bed deformation caused by an abrupt slip at the India/Burma plate interface. 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). From the deformation contour, it is seen that the estimated uplift and subsidence zone is between 92° E to 97°E and 2°N to 15°N with a maximum uplift of 5.07 m at the west and maximum subsidence of 4.74 m at the east (Fig. 1). In the source zone of Indonesian tsunami 2004, an appropriate value of sea surface rise/fall has been assigned as initial condition to each ζ-point of the staggered grid system. Since the pole is considered as on land, where no computation is done, there is no problem of instability during numerical computation.

4. TIDE AND TSUNAMI INTERACTION PRINCIPLE

In order to simulate the tide and tsunami interaction, the initial step is to generate the exact tidal oscillation during a tsunami period in the model basin by prescribing the appropriate sea surface elevation along the open boundary. This provides the initial sea-state condition for the interaction process. It is required that at the time of introducing the tsunami source in the model simulation process the tidal response, already generated, must match with the tidal oscillation in the actual basin. To incorporate the effect of tsunami, it is required to activate the tsunami source and to allow the propagating tsunami wave across the analysis area. In the Malacca Straits *M*2 and *S*2 constituents are predominant, so that in the spring-neap cycle there is significant variation of the tidal range. The diurnal inequalities (difference in heights between two successive high/low waters) with respect to high/low waters are also significant (Fig. 2). Moreover, due to the superposition of tidal constituents of different periods, the tidal oscillation is not exactly periodic. Thus the complexity associated with tidal phenomena leads to the difficult task of generating the exact tidal oscillation in the model basin.

Instead of generating such a complex oscillatory system, a relatively simple procedure is adopted. This leads to an oscillatory tidal solution with period of *M*2 constituent where the computed high water at each location is in agreement with the average of high waters predicted in the tide table for the tsunami period. For interaction purpose, the tsunami source would have to be activated at a particular time, say $t = T_0$, into the initially generated tidal oscillation. Let the tsunami wave approach the coast at time, say $t = T$. Now the procedural requirement is to adjust the time $t = T_0$ with such a phase of the tidal oscillation that at the time $t = T$ the phase of pure tidal oscillation at each location is in agreement with that in the actual basin.

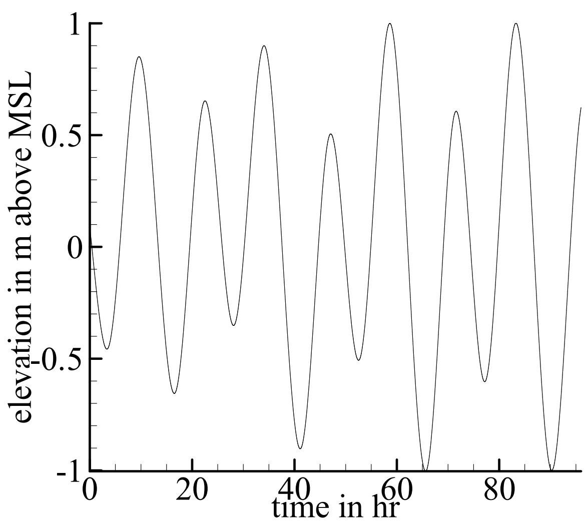

Figure 2. Computed water level due to tide at George Town (North-East coast of Penang Island).

5. INTERACTION METHODOLOGY FOR INDONESIAN TSUNAMI 2004

To investigate the influence of tidal phenomenon on tsunami wave height along the coastal belts of Penang Island associated with the Indonesian tsunami 2004, three model runs were set up:

- only tsunami wave
- tsunami wave input during high tide
- tsunami wave input during low tide

For the purpose of analysis, the results are presented in various forms at two coastal locations; one at north-west coast and another at George Town (north-east coast) of Penang Island, where tidal information are available in Malaysian tide table. The Indonesian tsunami 2004 arrived at north-west coast at the time of high tide and arrived at north-east coast at the time of low tide. For computing water level due to superposition or interaction at a particular location, tidal information of that location must be available. For the purpose of interaction/superposition of tide and tsunami at a coastal location, the time series of tide at that location is necessary. But in general, the tidal information is available, as high and low values, four times a day in the tide table of Malaysia. The corresponding time series is generated through a cubic spline interpolation method. Figure 2 represents the tidal information at George Town situated at the north-east Coast of Penang Island.

The tide is generated in the model domain through the west open sea boundary condition (6) with appropriate values of a, T and φ in absence of tsunami. It is observed from the tide table that though there is variation in the tidal period at the head of Penang Sea, the average period is approximately of $M2$ tide and so we chose T = 12.4 hours and φ = 0. The information of the tidal amplitude along the west boundary is not available. We have chosen a = 0.8 m to test the response of the model along the coastal belt. The response is found to be sinusoidal with the same period (12.4 hours). But the amplitude at every location may not be exactly same in reality. By providing appropriate values of the amplitude of a, and phase φ along the western open sea boundary, the model is expected to generate representative tidal oscillation in the whole basin.

6. RESULTS AND DISCUSSIONS

Figure 3 depicts the time series of water level due to tsunami (only) at a coastal location (north-west coast) of Penang Island. The arrow (in the horizontal axis) indicates the time of initiating the tsunami source. The maximum elevation is approximately 3.1 m. The time series of water level at the same coastal location due to the interaction of high tide and tsunami is presented in Fig. 4. The tsunami source is activated in such a phase that tsunami wave arrives at the north-west shore of Penang when the tidal amplitude achieves maximum (during high tide). It is seen that major oscillation occurred during high tide period. Due to the interaction of tsunami with high tide the water level is found to be more (3.4 m) than that due to tsunami only (Fig. 3). Thus tide has significant effect on water height along the coastal belt.

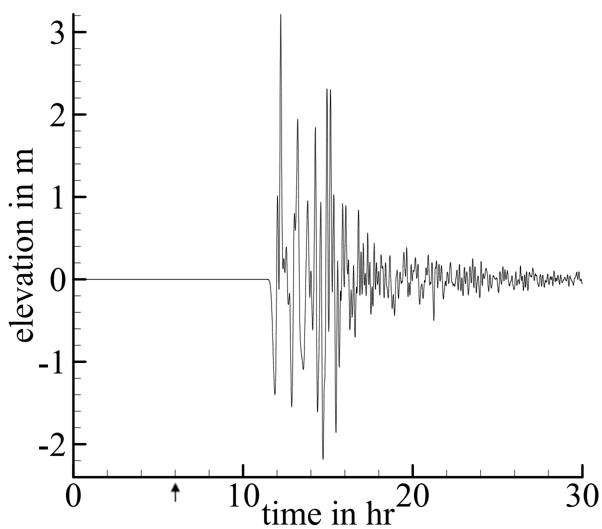

Figure 3. Time series of water level due to tsunami only at north-west coast. The arrow indicates the time of initiating the tsunami source.

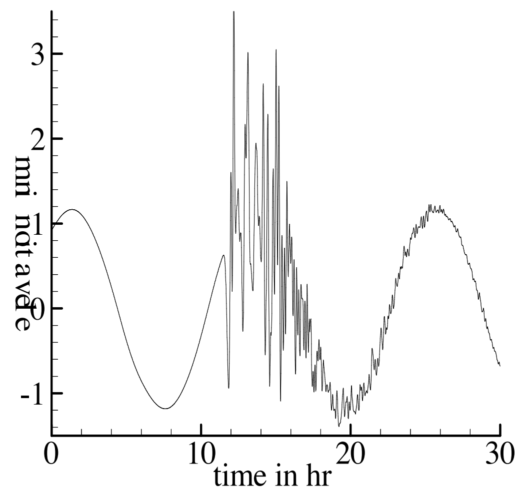

Figure 4. Water level due to interaction of tsunami and high tide at the same coastal location.

In order to investigate the significance of non-linear interaction of tide and tsunami, comparisons is done between superposition of tide and tsunami and nonlinear interaction of tide and tsunami. Figure 5a shows the time series of water level obtained by superposition of tide and tsunami (tide + tsunami) at the North- west coast of Penang Island. This is obtained by superimposing linearly the time series of tsunami response obtained through model simulation and that of tidal oscillation obtained from tide table (Fig. 2). Figure 5b shows the time series of water level due to the nonlinear interaction of tide and tsunami at the same coastal location. Comparison shows that oscillation is identical but with different amplitude. It is seen that superposition gives the over estimation of water level. So, it is important to compute non-linear interaction near the beach.

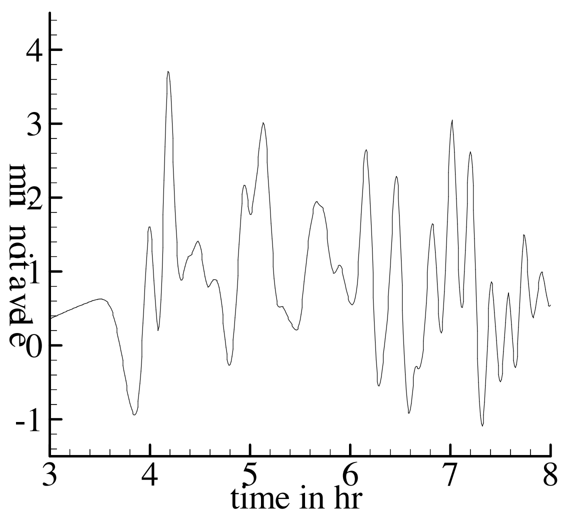

Figure 5a. Water level due to superposition of tide and tsunami (tide + tsunami) at north-west coast of Penang

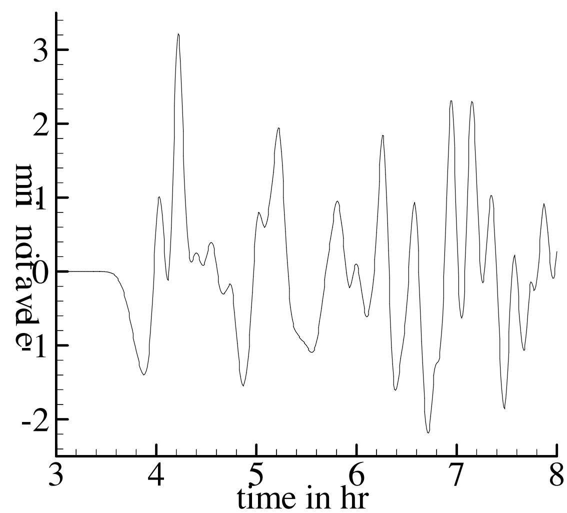

Figure 5b. Water level due to nonlinear interaction of tide and tsunami at the same location.

The influence of tide on tsunami is also investigated. Figure 6a show the water level at the same coastal location of Penang Island due to tsunami only. On the other hand, the water level at the same location is obtained by subtracting tide from tide and tsunami interaction (tide and tsunami interaction – tide) and presented in Fig. 6b. Since both the curves are not identical, it follows that the tide has a significant effect on ultimate tsunami response along the coastal regions.

Investigation on the influence of low tide on tsunami has been carried out at George Town. In this computation tsunami source is activated in such a phase that tsunami wave arrives at the north-east shore when the tidal amplitude reaches to minimum (during low tide). Figure 7 show the interaction of tide and tsunami at George Town. The surge response due to interaction of tide and tsunami during low tide period is found to be less (1 m) than that due to tsunami surge only.

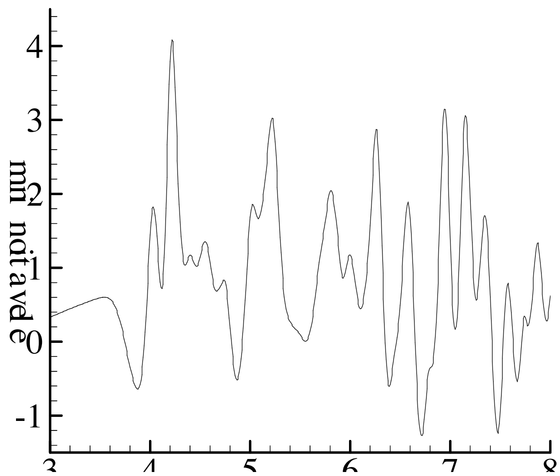

Figure 6a. Time series of water level due to tsunami at a coastal location of Penang Island.

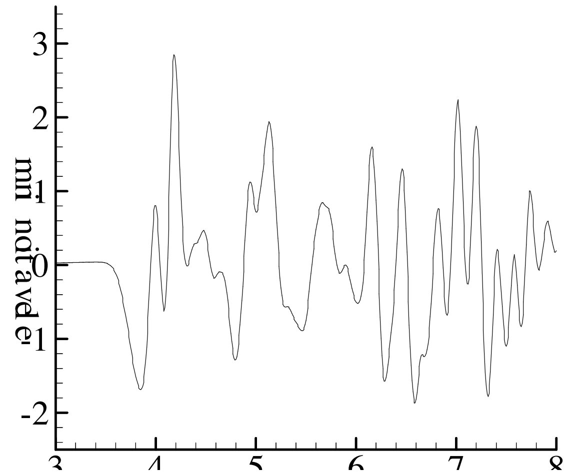

Figure 6b. Water level due to tide, tsunami interaction – tide at the same coastal location.

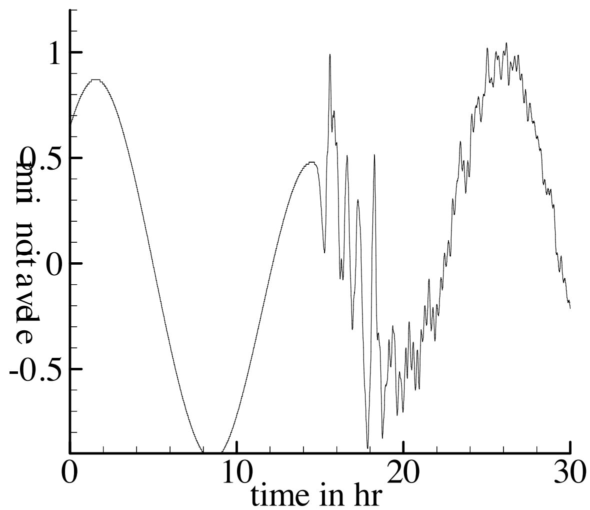

Figure 7: Water level due to the interaction of tide and tsunami at north-east coast.

A post tsunami survey report for some coastal locations of Penang Island, done by the authors, is available in Roy et al. (2007b). Computed results at two coastal locations are found to be in good agreement with the observations. Figure 8 depicts the computed maximum water levels due to tide and tsunami interaction during the high tide period along the west coast of Penang Island, where the maximum elevation is found to be 5 m. The surge intensity is found to be higher at the north-west coast. On the other hand, the maximum water levels due to tide and tsunami interaction during low tide period along the west coast are found to be 3.6 m (Fig. 9). Thus, tide has a significant effect on tsunami enhancement along the coastal regions.

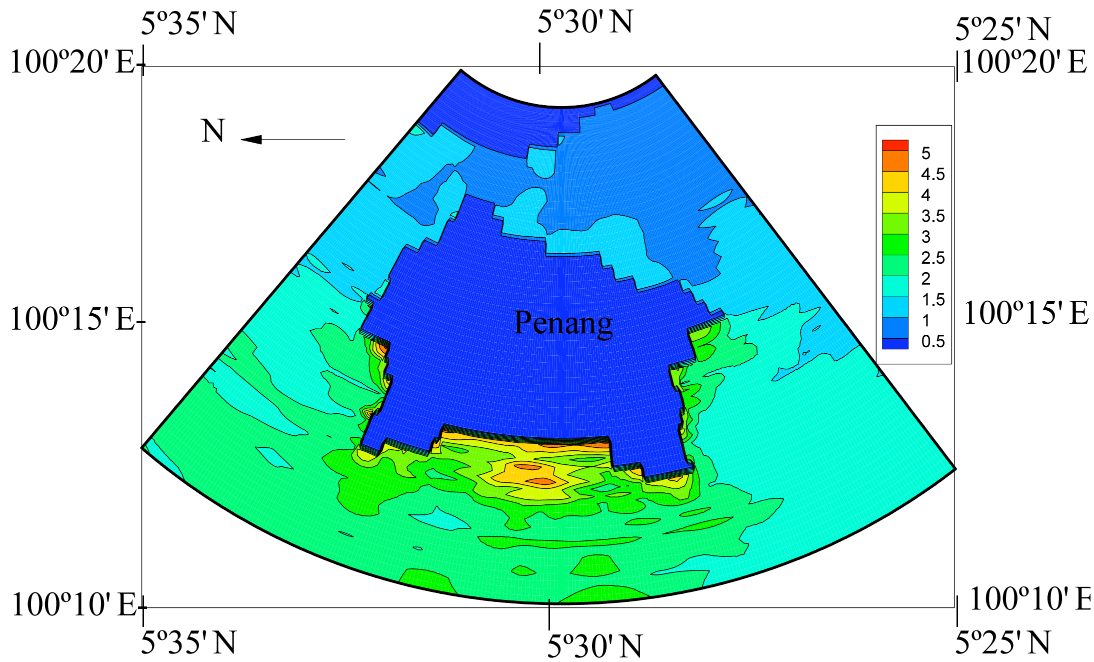

Figure 8. Maximum elevation along the coastal belts of Penang Island during high tidal period

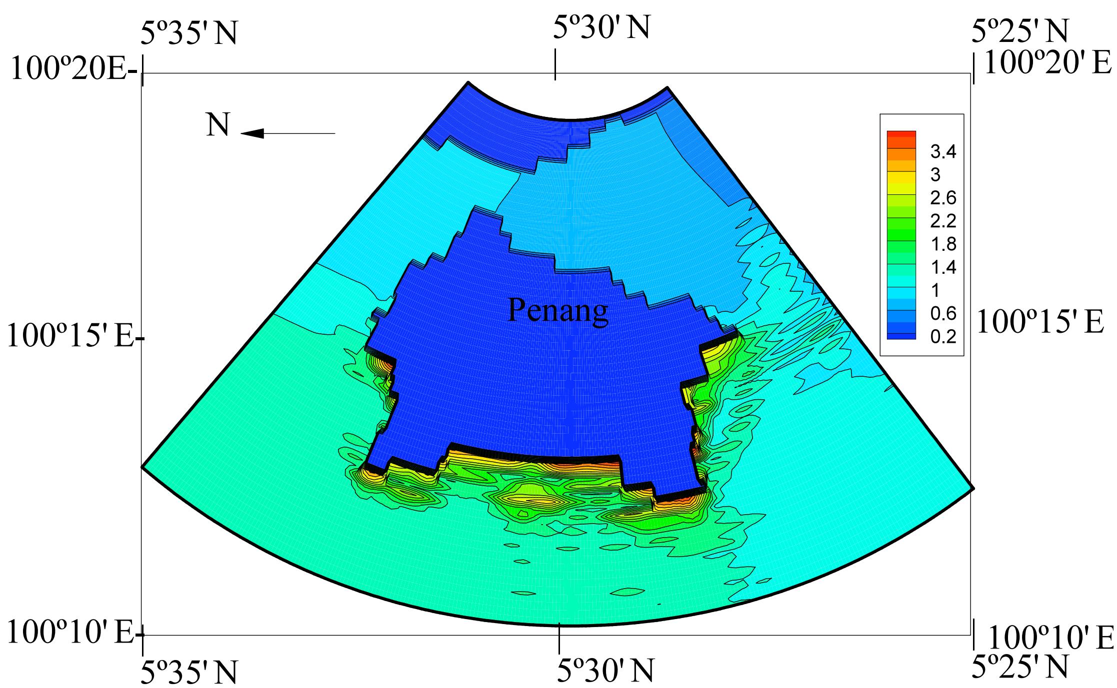

Figure 9. Maximum elevation along the coastal belts of Penang Island during low tidal period

7. CONCLUSION

It has been shown that the astronomical tides have significant effect in tsunami enhancement in the coastal regions. The nonlinear interaction of the tide with tsunami is important, as it generates stronger sea level changes along a coast. So for accurate prediction of tsunami along a coastal belt, it is necessary to consider the tidal effect on tsunami.

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