Tsunami run-up amplification factors for real-time prediction of run-up heights and inundation distances for Penang Island

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Abstract. The mega Indian Ocean tsunami that struck Malaysia on 26 December 2004 has awakened the attention of Malaysian government to implement appropriate risk reduction measures, including timely and orderly evacuation. Certain beaches in Penang have been identified as highly vulnerable to future tsunamis originating from the Andaman Sea. To determine the evacuation zones and routes, the height of the tsunami waves penetrating the beaches must be predicted in advance. However, real-time model simulations are too time-consuming for timely predictions. Therefore, in this study, an approach of applying run-up amplification factors to estimate the run-up heights is conducted to provide a simple and reliable way to obtain real-time estimation of the run-up heights. This is performed by multiplying the run-up amplification factors with the offshore incident wave heights detected or simulated by tsunami early warning system. Model simulations are performed using the in-house model TUNA-RP to obtain the run-up amplification factor and inundation distance for Penang Island. Model simulations show that the run-up amplification factors are mainly determined by the near-shore bathymetry and topography, as well as by the incoming tsunami wave heights and the incoming wave directions. The comparison between measured tsunami wave heights for the 2004 Andaman tsunami and estimated run-up heights derived from run-up amplification factors demonstrates good agreement. The estimated run-up amplification factors may be used to obtain rapid estimation of the inundation distances along the coastline of Penang Island. A comprehensive inundation map of Penang Island that could be used for rapid determination of evacuation zones is presented. The inundation distances and run-up amplification factors produced in this study would be useful to disaster and emergency managers for planning evacuation and managing coastal development.

1. Introduction
The devastation inflicted by the 2004 Indian Ocean tsunami in Malaysia caught the attention of Malaysian government as well as its research communities. Various mitigation research and resilience strategy have since been developed to reduce the potential tsunami risks. This includes the development of a numerical simulation model, TUNA [1] to simulate the three phases of tsunami dynamics—generation, propagation as well as run-up and inundation. Numerical models are essential tools for forecasting the tsunami arrival times, run-up heights and inundation distances in a tsunami event. This information is important for a timely and effective evacuation of the coastal communities to safer grounds or nearest designated emergency shelters. In order to develop a tsunami early warning system, pre-computation of tsunami wave run-up is necessary because the simulation of tsunami, particularly the run-up and inundation phase, is too time-consuming for real-time predictions. The predictions of tsunami arrival times, run-up heights and inundation distances in actual tsunami events are expedited by developing pre-computed tsunami database. The pre-computed tsunami database
contains the information of tsunami propagation in deep ocean from a collection of potential
tsunamiogenic sources. These potential sources are typically tsunamiogenic earthquake sources located
along known and potential earthquake zones. Some sources that are unrelated to earthquake and are
not acknowledged in the database might have been missed or omitted. This might compromise the
ability to predict the tsunami run-up and inundation of the previously undefined sources in real time
during actual tsunami events. An alternative is the employment of the run-up amplification factor that
estimates the run-up heights based upon characteristics of incident wave and bathymetric slope. The
approach of applying run-up amplification factors to estimate the run-up heights is a simple and
reliable way to obtain quick estimation of the run-up heights by multiplying the run-up amplification
factors with the offshore incident wave heights detected by deep ocean tsunami buoys and tide gauges.
It can be a complement to the existing pre-computed tsunami database and act as a quick tool to
estimate the inundation distances. Run-up amplification factors are computed by means of an in-house
model simulation TUNA based upon credible tsunamiogenic earthquake source scenarios derived from
tectonic activity around the region to provide the estimation of tsunami run-up heights and inundation
distances.

2. Tsunami-tracking Utilities aNd Application TUNA
TUNA-RP is an in-house tsunami numerical model developed based upon the non-linear shallow
water equations (NSWE) coupled with moving boundary algorithm. The continuity and momentum
equations of the depth-averaged two-dimensional NSWE [2, 3] are described in equations (1) to (3).
The definition and unit of symbols used in equations (1) to (3) are listed in Table 1. The governing
equations are solved using the explicit leap-frog finite difference scheme with an upwind algorithm for
the nonlinear advection terms. Moving boundary algorithm is applied to track the movement of
shoreline as the tsunami rises or recedes and predicts the maximum run-up heights of tsunami along
the coast. Details of the mathematical formulation and moving boundary algorithm applied in TUNA
are available in [4, 5].

For tsunami forecasting, improper prediction of a numerical model may lead to fatality or
unnecessary evacuations. Therefore, model verification and validation are necessary to assess the
predictive capability of the model. Comparison between numerical results and benchmark analytical
solutions, laboratory experiments as well as field measurements is a common way to validate and
verify the performance of a numerical model. The in-house tsunami run-up and inundation model,
TUNA-RP has been successfully validated and tested through comparison with analytical solutions as
well as with laboratory experiments based upon several standardized benchmarking cases recorded in
the National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum OAR
PMEL-135 [6]. The details of TUNA-RP verification and validation are available in Koh et al. [7].

\[
\frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0
\]

(1)

\[
\frac{\partial U}{\partial t} + \frac{\partial U}{\partial x} \left( \frac{U^2}{h} \right) + \frac{\partial V}{\partial y} \left( \frac{UV}{h} \right) + g h \frac{\partial \eta}{\partial x} + \frac{g n^2}{h^{7/3}} U \sqrt{U^2 + V^2} = 0
\]

(2)

\[
\frac{\partial V}{\partial t} + \frac{\partial U}{\partial x} \left( \frac{UV}{h} \right) + \frac{\partial V}{\partial y} \left( \frac{V^2}{h} \right) + g h \frac{\partial \eta}{\partial y} + \frac{g n^2}{h^{7/3}} V \sqrt{U^2 + V^2} = 0
\]

(3)

| Symbol | Unit | Definition |
|--------|------|------------|
| \( t \) | s    | Time       |
| \( x \) | m    | Space coordinate along x- direction |
| \( y \) | m    | Space coordinate along y- direction |
| \( \eta \) | m    | Free surface elevation measured from a fixed datum (mean sea level) |
| \( h \) | m    | Total water depth, \( h = \eta + d \) |
| \( d \) | m    | Water depth below fixed datum |
**3. Tsunami risk for Penang Island**

Subduction zones are boundaries where two tectonic plates converge and where one plate thrusts beneath the other. This process could result in geo-hazards such as earthquakes and volcanoes, particularly in regions around the edges of the Pacific and Indian Ocean, where the major subduction zones are located. A powerful earthquake, called a megathrust earthquake, may occur at the interface between the two plates. The Indian Ocean earthquake that occurred on 26 December 2004 is an undersea megathrust earthquake that triggered a series of devastating tsunamis. Malaysia is largely protected from tsunami originating from the Sunda subduction zone due to its favourable geographical location, sheltered from tsunami sources by the Sumatra Island. However, Northern Peninsular Malaysia faces a certain degree of tsunami hazards from the most seismically active plates between the Indo-Australian Plate and the Eurasian Plate (more specifically, the Sunda Plate). The 2004 tsunami caused by this earthquake claimed 68 lives along the northwestern coasts of Peninsular Malaysia [8].

The plausible tsunamigenic earthquake region capable of generating tsunamis that will strike Northwestern Peninsular Malaysia is along the Northern Sumatra northwards to Andaman-Nicobar Islands (figure 1). The Andaman-Nicobar region located at the north of Sunda Arc is a seismically active zone and frequently generates tsunamigenic earthquakes, for instance in year 1847 (Mw >7.5), 1881 (Mw 7.9) and 1941 (Mw 7.7) [9]. Figure 1 illustrates the regional map of Sumatra subduction zone and rupture areas of these past earthquakes. According to Bapat [10], from years 1900 to 1980, a total of 348 earthquakes occurred in the region bounded by latitude 7.0°N to 22.0°N and longitude 88.0°E to 100°E with moment magnitude (Mw) ranging from 3.3 to 8.5. Nevertheless, only five of these earthquakes are tsunamigenic with Mw ≥ 7.1 [11]. After the rupture of 2004 and 2005 earthquakes, the Northern Sumatra and Andaman-Nicobar regions are estimated to be probably free from great earthquakes (Mw ≥ 8.0) for a few decades [9, 12]. The lower bound return period of great earthquakes that are similar to the 2004 megathrust events are approximated to be 400 years [13, 14]. The largest credible earthquake of Mw 8.5 or higher that we should be prepared for in the next 50-100 years is a tsunamigenic earthquake along the Sunda Arc subduction zone. This tsunami could strike Thailand and Northwestern Peninsular Malaysia with an estimated return period of 200 years [15, 16]. On the other hand, there is a high probability for seismicity in the region between south Andaman and Arakan. The Global Positioning System (GPS) survey has provided information that shows earthquake of Mw 8.5 (every century) or Mw 9 (every 500 years) at the Arakan (Myanmar) subduction zone [17]. Further, according to Cummins [18], a potential tsunami generated by submarine landslide could take place at the Bay of Bengal due to the rapid rate of sedimentation in the region.

Although the recurrence interval of great earthquakes derived from convergence rate at the Northern Sumatra and Andaman sea regions is large, the likelihood of potential tsunami threat around the region cannot be neglected, as earthquakes are highly unpredictable even with the current technology. For example, before the 2004 tsunami event, seismologists believed that great earthquake and tsunami hazards would not occur in the Sumatra-Andaman region. Therefore, it is important to continuously revise our understanding of tsunami, improve tsunami mitigation and tsunami early warning system as well as anticipate future tsunami threats.

### Table

| Symbol | Unit | Description |
|--------|------|-------------|
| g      | m/s²| Gravitational acceleration |
| n      | s/m² | Manning’s relative roughness coefficient |
| U      | m/s | Discharge fluxes in the x-direction |
| V      | m/s | Discharge fluxes in the y-direction |
Figure 1. Regional map of Sumatra subduction zone and rupture areas of past great earthquakes [13]. Red line is the inter-plate thrust that intersects the sea floor along the Sunda Trench. Light yellow shaded area indicates the possible region where tsunami generated by earthquake will strike Northern Peninsular Malaysia. Yellow ellipses show the rupture of 1847, 1881, 1941 earthquakes. Red circle represents the epicentre of 2004 earthquake and the dotted line marks the rupture zone.

Figure 2. Direction of the incoming tsunami waves propagating from the west (a) and northwest (b) directions towards Penang Island.

From the review above, it is conceivable that potential future tsunamis will most likely strike Penang Island with incoming tsunami waves from the west and northwest directions. Therefore, model simulations that consider incoming tsunami wave from the west and northwest directions (figure 2) of Penang Island are performed to obtain the run-up height and to compute the run-up amplification factor along the entire coast of Penang Island. The model used is the in-house two-dimensional tsunami run-up and inundation simulation model TUNA-RP. The offshore incident wave form used for simulations of both incoming wave directions is a solitary wave with three wave amplitudes of 1, 2 and 3 m and one wavelength of about 20 km. In the simulations, the simulated maximum run-up heights along the coastline of Penang Island are recorded to obtain the run-up amplification factors.

4. Results and discussion

4.1. Run-up amplification factors for Penang Island

The run-up amplification factor is defined as R/H, where R represents the run-up height and H represents the offshore incident wave height. Offshore incident wave height is the height of incoming wave at offshore. The obtained run-up amplification factors for different incident wave heights and incoming wave from the west and northwest directions of Penang Island are used to obtain the comprehensive run-up amplification factors for Penang Island, as summarized in figure 3. The run-up amplification factors along the west of Penang coast are higher than the run-up amplification factors along the north coastline of Penang mainly because the west coast lies directly in the propagation path of the tsunami waves. At the northeast and south of Penang Island, the amplification factors may reach 3. This implies that an incident wave with amplitude of 2.0 m at offshore deep water will likely be amplified to a run-up height of 6.0 m in the areas where coastal reclamation is currently ongoing or are planned. A run-up height of 3.0 m is commonly regarded as highly dangerous to human life. A run-up
height of 6.0 m is considered very dangerous. Hence, the Penang state government should seriously review its policy and permits on coastal land reclamation in Penang Island, particularly at the northeast and south of Penang Island.

Figure 3. Comprehensive distribution of run-up amplification factors along the coastline of Penang Island derived from the run-up amplification factors for the west and northwest incoming tsunami wave directions towards Penang Island and three incident wave heights of 1, 2 and 3 m.

Figure 4. Simulated 2004 tsunami inundation distance (yellow) and estimated inundation distance (red) based upon the derived comprehensive run-up amplification factor.

4.2. Comparison with simulated inundation map and surveyed runup heights
To assess the reliability of the derived amplification factors for Penang Island, the run-up heights estimated by the comprehensive amplification factors for Penang are compared with the 2004 tsunami surveyed values. Table 2 shows the surveyed and the estimated run-up heights at five selected beaches in Penang. The comparison between surveyed and estimated run-up heights shows reasonable agreement in almost all areas except at Pantai Acheh. The plausible reason causing this discrepancy at Pantai Acheh is the exclusion of mangrove forest in the simulation. It has been documented that mangrove forests have the ability to reduce the ferocity of tsunami waves. Mangroves were found at the north-western coast of Penang, mainly near Pantai Acheh [19]. Several research studies have shown that the existence of coastal forest offer some degree of tsunami wave reduction [20–22]. In particular, Teh et al. [23] has derived a simple analytical formula to estimate the reduction in run-up heights due to the presence of mangrove forests. Considering the presence of mangrove forest at Pantai Acheh, Kh’ng et al. [24] reported a reduction ratio of 0.54 with a wave period of 60 minutes for the 2004 Sumatra tsunami waves. Kulikov [25] stated that the wave period for the Sumatra tsunami waves is around 50 to 60 minutes. Hence, the estimated run-up height of 4.2 m at Pantai Acheh without mangroves should be reduced to 2.268 m with the presence of the 1-km width mangrove forests. This mangrove-adjusted run-up height compares well with the surveyed run-up height of 2.51 m at Pantai Acheh.

To examine the reliability of the comprehensive run-up amplification factors acquired based upon possible incoming tsunami wave directions towards Penang Island, the inundation map obtained using these comprehensive run-up amplification factors is compared to the simulated 2004 tsunami
inundation map. Hereafter, estimated inundation distance refers to the result calculated using the derived run-up amplification factors, while simulated inundation distance refers to the result produced through the complete model simulation of tsunami evolution from its generation at source to its propagation in the deep sea and finally its runup onto shore. It was reported that the 2004 tsunami propagated towards Penang Island with an offshore wave height of around 1 m [1]. Hence, using the comprehensive run-up amplification factors presented in figure 3, an estimated inundation map is produced. This estimated inundation map is then compared to the simulated inundation map of Penang Island for the 2004 tsunami. The simulated inundation map is obtained through the complete model simulation of the 2004 tsunami, starting from its generation at source to its propagation in the deep sea and finally its runup onto the coasts of Penang. The comparison of this estimated and simulated inundation map is shown in figure 4.

Table 2. Surveyed [1] and estimated run-up heights in Penang.

| Location              | Lat (°) | Long (°) | Run-up Height (m) | Surveyed (2004 tsunami) | Estimated by R/H |
|-----------------------|---------|----------|-------------------|-------------------------|-----------------|
| B. Ferringhi (Teluk Bayu) | 5.47    | 100.24   | 3.46              | 3.60                    |
| B. Ferringhi (Miami Beach) | 5.48    | 100.27   | 4.00              | 4.50                    |
| Tanjung Tokong        | 5.46    | 100.31   | 2.61              | 2.20                    |
| Tanjung Bungah        | 5.47    | 100.28   | 2.31              | 2.20                    |
| Pantai Acheh          | 5.40    | 100.18   | 2.51              | 4.20                    |

A statistical hypothesis test, T-test, is performed to assess the difference between the estimated inundation distances and simulated inundation distances for the 2004 tsunami. Note that in T-test, a p-value that is smaller than 0.05 indicates strong evidence that there is significant difference between two sample means. The T-test returns a p-value of 0.64, which is greater than the threshold value of 0.05 that indicates no significant difference for the two-sample means, except for the inundation distances along the west coast of Penang Island. The T-test results showed that the p-value for the inundation distances at the west coast of Penang Island is less than 0.001, which implies that there is a significant difference between the simulated and estimated inundation distances at the west coast. This is mainly because the presence of the mangrove forest is not considered in the derivation of the run-up amplification factors used to produce the estimated inundation map. The presence of this mangrove forest is, however, included in the 2004 tsunami simulation that produces the simulated inundation map. Nevertheless, the estimated inundation map appears to compare well overall with the simulated inundation extent of the 2004 Tsunami. This means that if this estimated inundation map had existed during the 2004 Tsunami event, it would have provided a quick and reasonable estimation of the inundation extent of the 2004 Tsunami for timely and effective evacuation.

5. Conclusion

This paper has presented run-up amplification factor as a useful tool for rapid preliminary assessment of tsunami hazards for Penang. Potential scenarios of tsunami run-up along the Penang coast due to megathrust earthquake originating from the Andaman Sea are simulated by means of TUNA-RP to obtain the run-up amplification factors and inundation distances for Penang Island. The run-up amplification factors are mainly influenced by the coastal topographic and bathymetric profiles, by offshore incident wave heights and propagating directions of incident wave. The comparison between the measured tsunami run-up heights for the 2004 Andaman tsunami and those estimated by the amplification factors derived from TUNA-RP model simulations demonstrates good agreement. An inundation map for Penang Island can be obtained rapidly during a tsunami event based upon the estimated arrival wave height issued by the Malaysian Meteorological Department (MetMalaysia). The generated inundation map provides a basis for the evacuation planners to decide on the evacuation zones to help the coastal communities evacuate timely and effectively during a tsunami event.

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