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Assessing potential impact of tsunami on Penang Island via TUNA-RP simulation

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Abstract The Indian Ocean mega tsunami that occurred on 26 December 2004 resulted in the death of over 200,000 people worldwide, including 52 deaths in Penang Island, Malaysia. This rare but devastating tsunami highlights the vulnerability to future tsunamis for Malaysian coastal communities living in affected areas. To assess the potential impact of future tsunami, numerical tsunami models are used to project the maximum inundation distances and maximum runup heights along the affected coastal areas. In this paper, the in-house one-dimensional tsunami runup model codenamed TUNA-RP is enhanced and used to investigate the relations between the steepness of beach slope and tsunami impact, specifically inundation distance and runup height. The simulation results of TUNA-RP show that the inundation distances and runup heights decrease exponentially as the steepness of beach slope increases. Inundation distance and runup height at seven high-risk coastal areas in Penang Island, such as Teluk Bahang, Batu Feringghi and Tanjung Bungah, are presented in this paper to highlight risks and vulnerability. At certain locations along Penang beaches, a worst-case scenario may result in a tsunami with runup heights of 10 m which is highly dangerous, that might potentially take the lives of hundreds or thousands. Recognizing this vulnerability to tsunami risks for Penang, further research is essential for developing tsunami resilience in the face of this tsunami hazard.

Keywords Runup; inundation; beach slope; tsunami amplification factor.

2010 Mathematics Subject Classification 74J30; 76B15.

1 Introduction

Two recent catastrophic tsunamis occurred in the past decade in the Asia-Pacific region. On 26 December 2004 the Indian Ocean tsunami shocked the world inflicting human deaths exceeding 200,000 worldwide. This rude wake-up call was repeated in 2011 when a giant tsunami struck the coasts of northeast Japan on 11 March, causing the death of more than 20,000 and totally destroying the Fukushima Daiichi Nuclear Power Plant. These two giant tsunamis motivated scientists and disaster reduction experts from different disciplines to work together with the goal of reducing the impacts of these destructive tsunamis. One important area of tsunami research is to predict and assess the potential impacts of future tsunamis by means of tsunami model simulations. The linear shallow water equations (SWE) have been proven to be capable of providing a good approximation to tsunami propagation across the deep ocean where the wavelength is much larger than the water depth and where the wave height is much smaller than the water depth. A rule of thumb for applying the linear SWE is that the water depth should be at least 10 times the wave amplitude. But as the tsunami waves propagate into the shallower water region, the wave celerity is reduced. Faster moving water column at the back of the tsunami pushes the slower moving water in front, resulting in increased wave heights in shallow regions, while the wavelength decreases. A relatively modest tsunami of around 1 m wave height in offshore deep water may amplify to wave heights of several meters, possibly reaching 6 m, striking the coastal areas with devastating force and inundating vast extent of low-lying areas. The SWE is no longer valid for this runup process, which is commonly modeled using the nonlinear SWE (NSWE) with moving boundary algorithm [1–3]. To provide a quick preliminary assessment of runup heights and inundation distances, one-dimensional NSWE is often used. The continuity and momentum equations of the nonlinear SWE in one dimension are described as follows.

$$\frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} = 0, \tag{1}$$

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x}\left(\frac{U^2}{H}\right) + gH\frac{\partial \eta}{\partial x} + \frac{gn^2}{H^{7/3}}U^2 = 0. \tag{2}$$

Here, U (m^2/s) is discharge flux in the x-direction, η (m) is water elevation above mean sea level, h (m) is the water depth below the mean sea level, t (s) is time, H (m) (= η +h) is total water depth, g (m/s^2) is the acceleration due to gravity and n (s/m$^{1/3}$) is the Manning's roughness coefficient. There are several schemes for solving the NSWE. In this paper, the NSWE are solved by using the explicit leap-frog finite difference scheme with an upwind algorithm used for the nonlinear convective term coupled with the moving boundary algorithm as described in Tan *et al.* [4]. With increased wave heights reaching several meters along the beaches, the runup and drawdown of tsunami can be very turbulent and extremely dangerous, capable of inflicting great loss of lives and causing vast destruction of coastal facilities. It is widely reported that runup height and inundation distance depend significantly on the beach profile, given a prescribed waveform at offshore deep water [5–9]. Mild slopes significantly amplify wave heights and greatly increase inundation distances. In this paper, we first simulate runup height and inundation distance as functions of beach slope, given a prescribed wave profile at deep water. For this purpose, the enhanced in-house one-dimensional tsunami runup model TUNA-RP is used [4,10]. We then present the simulated wave amplification factors for various beach profiles at selected high-risk coastal areas in Penang Island. The amplification factors, varying between 1 and 5 for Penang, serve as a simple rule of thumb guideline to provide initial assessment of tsunami risks, given a known wave profile of incident tsunami at offshore deep water. Where tsunami risks are predicted to be high, further refined analysis and simulation in two dimensions are then performed to provide detailed description of tsunami impacts at specific locations, useful for developing tsunami resilience for the protection of coastal communities.

2 Planar beach runup

The relationship between beach steepness and runup height or inundation distance is investigated here by varying the beach slope profiles. Steepness or slope is measured as the ratio of vertical height difference (m) to horizontal distance travelled (m). Land slope refers to the slope of the dry land region, while underwater slope denotes the slope of beaches below the Mean Sea Level (MSL). The combination of underwater slope and land slope characterizes the beach slope. Figure 1 illustrates schematically tsunami runup onto a planar beach with underwater slope of $h_{\mathrm{W}}/d_{\mathrm{W}}$ and land slope of $h_{\mathrm{L}}/d_{\mathrm{L}}$.

Simulations are performed for three scenarios. In Scenario 1, we maintain the profile where land slope = underwater slope, while varying the beach steepness. For Scenario 2, we vary only the land slope keeping constant underwater slope of 1/20. For Scenario 3, we vary only the underwater slope while keeping land slope fixed at 1/20. The slope of 1/20 is used as the reference steepness because the steepness of 1/20 is considered as an average slope which is observed most frequently worldwide. Following the practice commonly used, the incident tsunami wave used in this paper takes the form of a solitary wave represented by the Gaussian hump $\eta = ae^{-(x/\sigma)^2}$. The value of a describes the tsunami wave amplitude, while the value of σ prescribes the shape of the wave. This incident tsunami chosen in this paper originates from the offshore deep water region of the study domain with amplitude $a = 1$ m and standard deviation $\sigma = 5000$ m (equivalent to 20 km in wavelength, $\sim 4\sigma$). This chosen tsunami wave form is appropriate for the tsunami wave at depth of 50 m offshore of Penang for the 2004 Indian Ocean tsunami. The simulated amplification factors and inundation distances for Scenarios 1 to 3 are presented in the following sections. The wave amplification factors, defined as $A = R/a$, is the ratio between the maximum runup height and the amplitude of incident wave at offshore deep water (Figure 1). The highest onshore vertical height above MSL achieved by the tsunami waves is known as the runup height R. Inundation distance I is the maximum inland horizontal distance travelled by the tsunami waves.

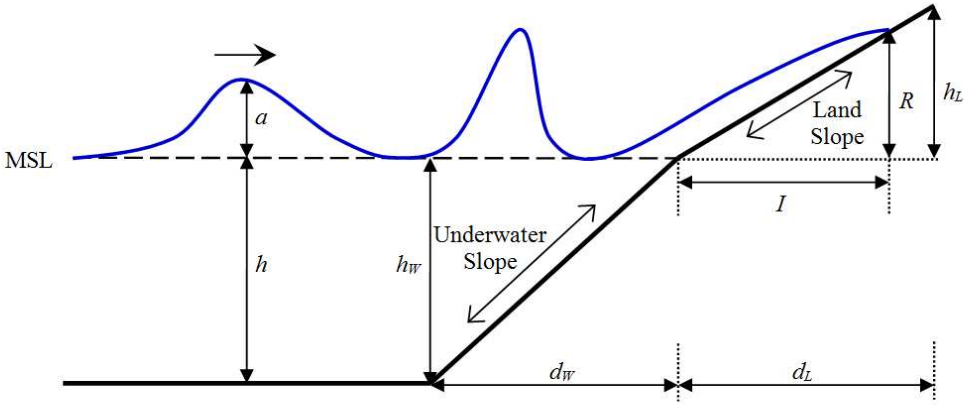

Figure 1: Schematic representation of tsunami propagation and runup onto a planar beach

2.1 Scenario 1: Varying beach slope

To recap, the beach slopes are varied by keeping land slope = underwater slope in Scenario 1. Figure 2 shows the amplification factors and inundation distances for various steepness of beach slope. The beach slopes considered in this paper vary between 1/100 and 2/5. A beach steepness of 1/100 (land slope = underwater slope = 1/100) indicates a mild slope whereas a slope of 2/5 signifies a steep beach slope. A mild steepness of 1/100 for both land and underwater slopes can amplify incident waves by a factor of almost 5, with an inundation distance of almost 1000 m. In previous studies by the authors for Penang beaches [11], the worst-case incident tsunami wave heights of around 2 m was observed from TUNA simulation up to the offshore deep water of 50 m depth. With an amplification factor of 5, a tsunami with incoming wave height of 2 m in offshore deep water might amplify to a maximum wave heights of 10 m along some parts of the Penang beaches. A tsunami wave height of 3 m observed during the 2004 Indian Ocean tsunami along the affected beaches in Penang has been recorded to have caused the loss of 58 lives. A tsunami with beach wave heights of 10 m is highly dangerous, and might potentially take the lives of hundreds or thousands. The amplification factors and inundation distances decrease exponentially with increasing beach slopes. Simulation results indicate that the amplification factors remain around 2.0 for slopes that are steeper than 1/10. The inundation distance is the longest for a mild slope of 1/100 while the steep slope of 2/5 results in the shortest inundation distance. This is because milder slope facilitates deeper inland penetration of wave.

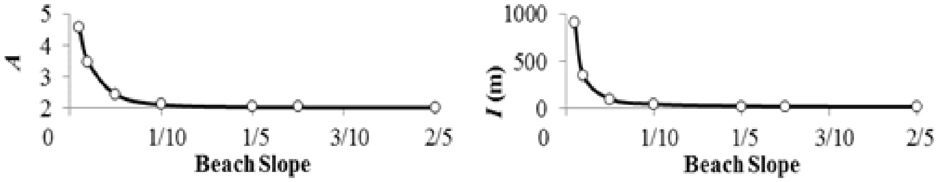

Figure 2: Amplification factor A (left) and inundation distance I (right) for various beach slopes

2.2 Scenario 2: Varying land slope

For this Scenario 2, the underwater slope is kept constant at 1/20 while the land slope is varied between 1/100 and 2/5. The amplification factors and inundation distances for various steepness of land slope are shown in Figure 3. Keeping the underwater slope constant at 1/20, the amplification factor reaches the highest value of 3.2 for land slope of 1/100. The amplification factors decrease exponentially, as land slope is increased from 1/100, approaching the constant value of 2.3 for land slopes greater than 1/10. The inundation distances increase exponentially with decreasing land slopes, reaching the longest inundation distance of 650 m for the land slope of 1/100. A tsunami wave amplification of 3.2 with an inundation distance of 650 m can inflict significant loss of lives and can cause severe property damage if the incident tsunami at offshore deep water exceeds 1.0 m, as was observed in Penang during the 26 December 2004 tsunami.

2.3 Scenario 3: Varying underwater slope

In this simulation Scenario 3, the land slope is kept constant at 1/20 while the underwater slope is varied between 1/100 and 2/5. Figure 4 shows the amplification factors and inundation distances for various steepness of underwater slope. Both the amplification factors and inundation distances decrease exponentially with increasing underwater slopes. For Scenario 3 with constant land slope of 1/20, the highest simulated amplification factor is

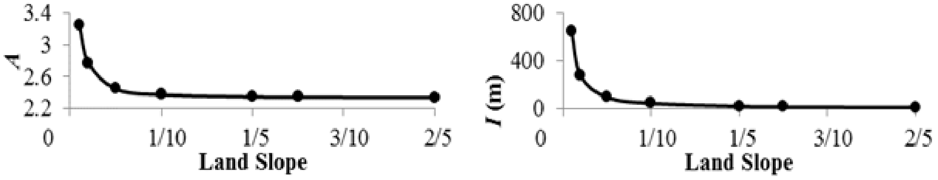

Figure 3: Amplification factor A (left) and inundation distance I (right) for various land slopes

about 3.6 for underwater slope of 1/100. The amplification factor remains around 2.0 for slopes greater than 1/10. It is noted that the amplification factor of 2.0 was assumed, based upon expert opinion, in Imamura et al. [12] for a beach with slope of 1/10. The maximum inundation distance is 140 m, with an underwater slope of 1/100. The inundation distances simulated for this scenario are significantly lower than those simulated in Scenarios 1 and 2. This is because the land slope is kept at a relatively steep slope of 1/20. In our simulation results, a slope with both land slope and underwater slope of 1/20 result in an amplification factor of 2.4. An underwater slope of 1/20 and land slope of 1/100 gives an amplification factor of 3.2. For land slope of 1/20 and underwater slope of 1/100, the amplification factor is 3.6. Mild underwater slopes allow more time for the wave to build up in height while mild land slopes allow the wave to penetrate further inland.

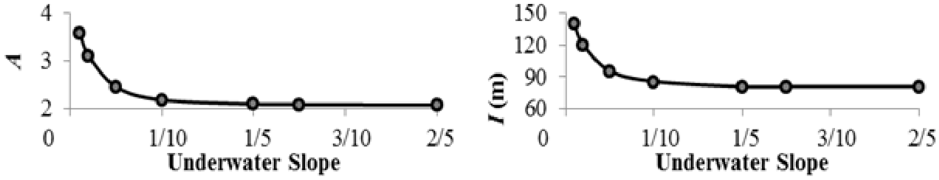

Figure 4: Amplification factor A (left) and inundation distance I (right) for various underwater slopes

3 Real runup in Penang

The 26 December 2004 mega Indian Ocean Tsunami left a devastating trail of destructions along the affected coastal areas in Penang, with 52 deaths out of 68 deaths for Malaysia. Recognizing the potential damage that Penang might receive from future tsunamis originating from the Andaman Sea, we performed a simulation study to evaluate the potential tsunami wave amplification factors at selected high risk spots in Penang Island. Based upon the field survey conducted by the authors after the infamous 2004 tsunami, seven high risk spots are selected for this purpose, namely (1) Gurney Drive, (2) Tanjung Tokong, (3) Tanjung Bungah, (4) Miami Beach which is located at Batu Feringghi, (5) Teluk Bahang, (6) Penang National Park and (7) Pasir Panjang Beach. The cross section for each of these locations is shown in Figure 5.

The computational domain was set up with a sufficient length for the solitary wave to

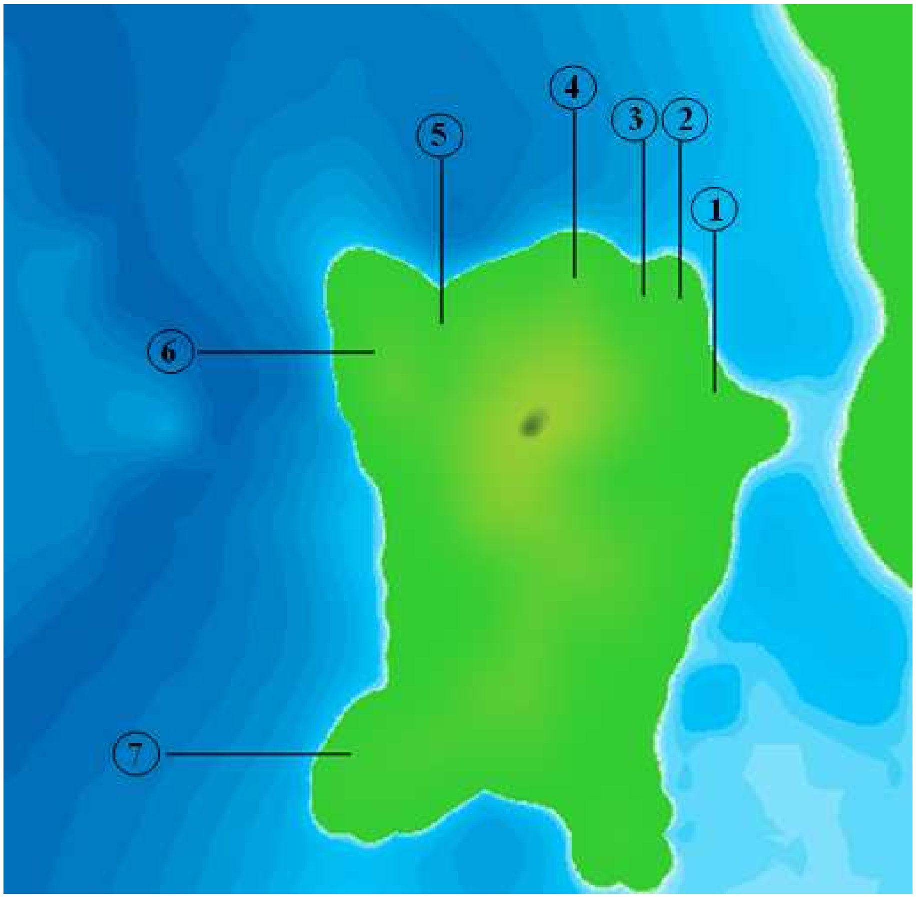

Figure 5: Study areas on Penang Island with bathymetry data

propagate from the deep waters into the shallow waters and finally onto the dry beach land. Solitary wave represented by a Gaussian hump with amplitude $a = 1$ m and standard deviation of 6000 m (wavelength $\sim$24000 m) is used as the incident offshore wave. The beach profiles for these selected spots are derived from the bathymetry and topography data from ETOPO1 provided by the National Geophysical Data Center (NGDC) of National Oceanic and Atmospheric Administration (NOAA). ETOPO1 is a one arc-minute ($\sim$1852 m) global relief model of the Earth's surface that integrates land topography and ocean bathymetry. The beach profiles for the seven high risk spots are displayed in Figure 6. The amplification factors and inundation distances for the seven locations are summarized in Table 1. Pasir Panjang Beach has the highest amplification factor of 2.84 as compared to the other locations. This is followed by Gurney Drive (2.58), Tanjung Bungah (2.49), Tanjung Tokong (2.46), Penang National Park (2.36) and Teluk Bahang (2.27). Among these selected locations, Miami Beach has the lowest amplification factor of 2.13. It should be noted that the ETOPO1 data is coarse grid, insufficient to provide high resolution local site-specific details required for more accurate simulation of runup along Penang Beaches. Based upon

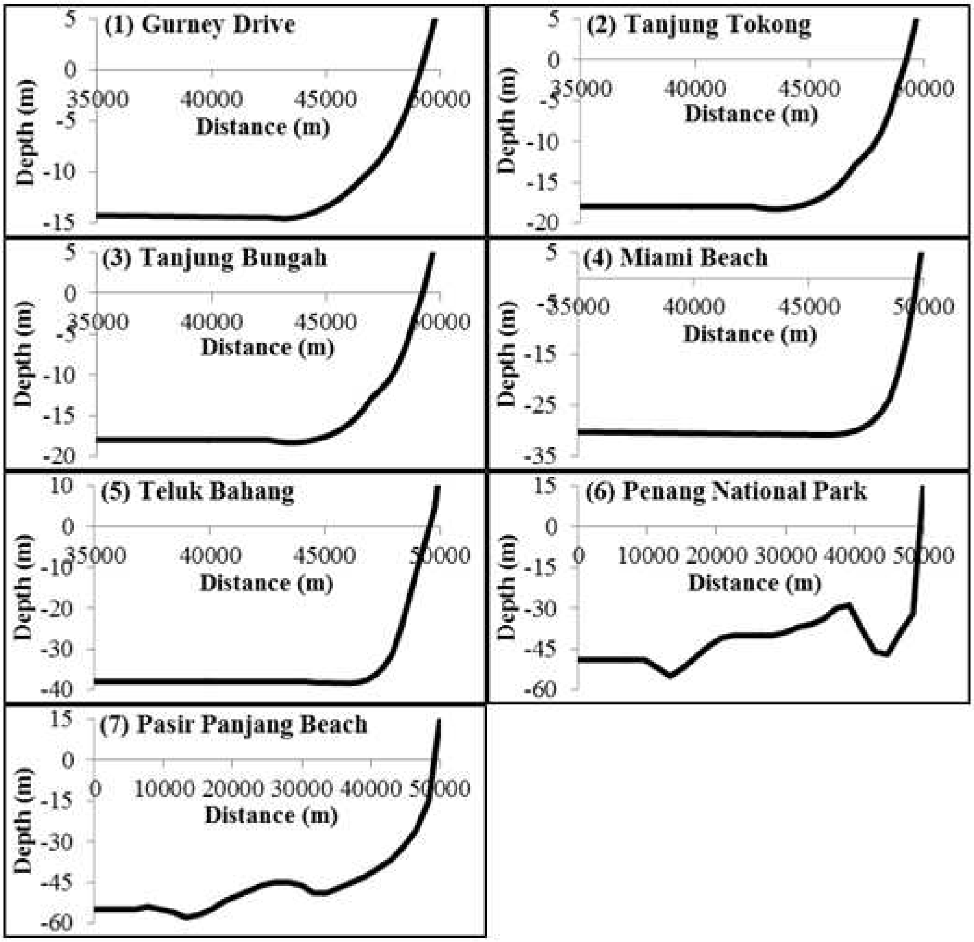

Figure 6: Beach profile of (1) Gurney Drive, (2) Tanjung Tokong, (3) Tanjung Bungah, (4) Miami Beach, (5) Teluk Bahang, (6) Penang National Park, (7) Pasir Panjang Beach

the survey conducted after the Indian Ocean tsunami, the wave amplification factor could reach 4.0 at some locations in Penang beach. For the purpose of verifying the accuracy of these numerically simulated amplification factors, we compile the measured data obtained from the US National Centers for Environmental Information (NCEI) from NOAA and Koh et al. [13] for comparison. These measured data for the selected locations mentioned in this study are compiled in Table 2. Further research is ongoing to further improve runup simulation by means of two-dimensional runup models using higher resolution topographic and bathymetric data in order to provide better information and insights for developing tsunami resilience in Penang.

Table 1: Amplification factor and inundation distance for the selected locations

No	Locations	Lat (N)	Long (E)	Amp Factor	Distance
1	Gurney Drive	5.4374	100.3092	2.58	320
2	Tanjung Tokong	5.4667	100.2991	2.46	210
3	Tanjung Bungah	5.4673	100.2890	2.49	240
4	Miami Beach	5.4783	100.2689	2.13	60
5	Teluk Bahang	5.4500	100.2151	2.27	110
6	Penang National Park	5.4500	100.1900	2.36	70
7	Pasir Panjang Beach	5.3000	100.1830	2.84	150

Table 2: Compilation of measured data obtained from NCEI and Koh *et al.* [13]

No	Locations	Lat (N)	Long (E)	Runup Height	Max Distance
1	Gurney Drive	5.4390	100.3080	2.50	200
2	Tanjung Tokong	5.4603	100.3080	3.65	35.8
3	Tanjung Bungah	5.4670	100.2770	2.50	—
		5.4700	100.2775	2.94	36.2
5	Miami Beach	5.4760	100.2660	3.00	10
		5.4778	100.2678	4.00	25.6
7	Pasir Panjang Beach	5.2950	100.1830	2.00	70

The offshore wave height for Penang as simulated by the tsunami propagation model [13] is about 1.0 m – 1.2 m. Using this offshore wave height of about 1.0 m and the amplification factors estimated in this study, the runup heights at (1) Gurney Drive is estimated as 2.58 m, (2) Tanjung Tokong is 2.46 m, (3) Tanjung Bungah is 2.49 m, (4) Miami Beach is 2.13 m, (5) Teluk Bahang is 2.27 m, (6) Penang National Park is 2.36 m, and (7) Pasir Panjang Beach is 2.84 m. The estimated amplification factors appear to fit measured data for some locations namely Gurney Drive and Tanjung Bungah. However, the simulated amplification factors for Tanjung Tokong and Miami Beach would provide runup heights that are less than the measured data at these two locations. For Miami Beach, there was a wall right behind the beach that might have caused wave reflected from the solid wall to interact with incoming waves to further amplify the wave heights, a factor that was not included in TUNA-RP. It should be noted that the observed runup values often differ from computed runup values by a factor of 2 or more [14,15,16]. Typically, runup amplification factor frequently varies between 2 and 3 [17] from wave heights computed at a depth of 50 m – 100 m. Depending on the local bathymetry and topography, the factor can range between 1 and 20.

The difference between the simulated and the measured results may be caused by several factors. The first factor is the simplified form of the offshore solitary wave of 1 m in amplitude and 24 km in wavelength for all selected locations. The 2004 tsunami waves arriving at the Malaysian shores are the leading depression N waves. It was shown in Tadepalli and Synolakis [18] that such waves produce higher runup heights than the solitary waves and leading elevation N waves. The second factor is the coarse resolution of the topography and bathymetry used in the simulations might put a limitation to the accuracy of the simulation. Runup heights and inundation distances are known to be highly dependent on bathymetry and topography along the flow path. Our simulation results are obtained based upon the bathymetry and topography data from ETOPO1. These data with resolution of $\sim$1.8 km are interpolated to fit the model resolution of 10 m. Previous studies [19,20] suggested that the amplification factor should be a function of computational grid size. Therefore, the simulated amplification factors should be taken as indicative values for preliminary assessment. A higher resolution bathymetry and topography should be used for more accurate projection of runup heights and inundation distances, for sites that have been identified as vulnerable. The third factor is the direction of the wave propagation. Here, we assume that the wave propagates perpendicularly to the coast. Finally, the fourth factor may arise from the manner runup heights and inundation distances are physically measured. The relevant data were measured at roughly the same locations as those we considered for the simulations but at slightly different spot. Further, field measurements of these data depend on the observed water marks, which may be subject to human bias during observation.

4 Conclusion

This paper presents some insights on the effect of beach slope on tsunami runup heights and inundation distances. Simulation results show that the inundation distances and runup heights decrease exponentially as the steepness of beach slope increases. Simulations were then performed to estimate the runup amplification factor at seven selected high-risk coastal areas in Penang Island. The runup amplification factor for Penang Island is estimated to be in the range of 2 – 4, depending on the local bathymetry and topography. Amplification factor serves as a quick assessment tool to approximate the potential runup heights based upon the computed tsunami amplitude at offshore deep water on a coarse grid system. However, the amplification factor needs to be estimated appropriately by comparing observed runup heights with computed tsunami amplitudes on various types of coasts.

Acknowledgements

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