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Langkawi Tsunami Hazards Mitigation and Inundation Maps

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Abstract: The immense sufferings following recent catastrophic Tsunamis call for an urgent need to develop resilience and hazards mitigation management capability among communities along the affected coastal regions. The 2004 Andaman mega Tsunami and the 2011 Fukushima Tsunami that triggered the triple disasters have one common feature: the lack of preparedness before the events and ineffective mitigation measures during and after the disasters. Effective and timely response by government agencies working closely with local communities plays an important role in reducing the adverse impacts. The ability to act decisively depends on the awareness, education and preparedness of local communities, working in close coordination with federal and local government agencies. In this study, we present Tsunami inundation scenarios in Langkawi Malaysia based upon TUNA-RP Model simulations derived from creditable assumptions regarding seismic activity in the region. Tsunami inundation distances and maximum run-up wave heights at several hotspots along Langkawi beaches are provided. Suggestions on practical procedures and basic principles for developing Tsunami mitigation for Langkawi will be discussed.

Key words: Langkawi, inundation maps, Tsunami resilience, mitigation, practical procedures, Langkawi

INTRODUCTION

Tsunamis are rare events but when they occur they inflict enormous damage, beyond the normal capability of communities to respond quickly and effectively, unless the communities are well-prepared in advance. The 2004 December 26 Andaman Tsunami killed a quarter million people worldwide including 68 persons in Malaysia. High attention is given by the Malaysian government in developing Tsunami hazards mitigation programs towards Tsunami resilience for coastal communities with particular reference to coastal areas badly affected by the 2004 Tsunami including Langkawi and Penang. Based upon current research observations, the task of building Tsunami resilience in Langkawi and Penang would be a challenge due to the low level of awareness in the communities. For example, on 12 September 2007, a Tsunami warning was issued for Penang, yet the people, choosing to celebrate the arrival of impending Tsunami along the beaches, defied police orders to evacuate from the evacuation zones in Penang. This defiance is a concern as the people should have been well aware that 52 lives were lost together with property damages amounting to more than RM 50 million during the infamous Tsunami that inflicted severe pain to Penang merely 3 years earlier. More recently on 16 September 2015, communities living in Tsunami hazards zones in Chile failed to observe evacuation order. Many could have been killed if the Tsunami had occurred. State of the art research has indicated that the next “Big One” is likely to occur any time soon. The unpredictable behavior and infrequent occurrence of earthquakes and Tsunamis dampen the sense of fear and vigilance which is the main cause of deaths during a Tsunami. Because of this little-known or almost unquantifiable risk regarding Tsunamis, Davies *et al.* (2015) advocated the development of Tsunami resilience at the local level based upon scenarios perceived as likely to happen in additional to macro-level federal planning. This study concurs with this view as developing resilience requires good collaboration and coordination at the community level between local communities, scientists and local government agencies. This Tsunami hazards mitigation program requires continuing efforts in monitoring, evaluation and reflection to reduce future losses through mitigation (Eisner, 2005). Public education on Tsunami risks, avoidance of new development in Tsunami prone areas, devotion of attention to building structural techniques and a comprehensive plan for evacuation are some urgent issues that need to be resolved. Tsunami

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prone areas may be identified from expert scientific opinion and Tsunami inundation maps. Recognizing the complexity in developing Tsunami mitigation capability, the US National Tsunami Hazards Mitigation Program (NTHMP) was tasked to develop a comprehensive approach that bolsters mitigation achievements to protect coastal residents and reduce future losses. The NTHMP is developed premised on the advancements in the science of Tsunami generation, propagation and run-up, on the improvements in Tsunami detection, warning systems and effect modeling and above all on public education (Bernard, 2005).

The NTHMP steering committee consists of representatives from the National Oceanic and Atmospheric Administration (NOAA), the Federal Emergency Management Agency (FEMA), the US Geological Survey (USGS) and the five Pacific coastal states of Alaska, California, Hawaii, Oregon and Washington. The NTHMP spends US$ 2.3 million per year tasked with the responsibility to reduce Tsunami hazards. NTHMP have successfully saved an estimated US$ 68 million by the timely cancelation of a false Tsunami warning that had avoided an otherwise mandatory evacuation. Inspired by the success of the NTHMP, Malaysia federal government allocated a total of RM20 million on a 5 years program for developing Tsunami hazard mitigation capability. The Malaysian Meteorological Department (MetMalaysia), the counterpart of US NOAA is tasked with the establishment and issuance of earthquake and Tsunami early warning while the National Security Council (NSC), similar to the US FEMA is responsible for implementation of relief measures for all disaster events. The first two researchers of this study have been appointed to develop Tsunami hazards modelling systems and human capability including Tsunami impact assessments for North West Peninsular Malaysia and East Malaysia. An Integral component of the Tsunami hazards mitigation project envisages that Malaysia Tsunami resilient communities and participating scientists must be able to identify hazard zones, develop inundation maps, disseminate evacuation maps and evacuate timely during a Tsunami (Bernard, 2005). As an integral part of this prerequisite of a Tsunami resilience community, this study is a continuing scientific contribution. Key elements of resilience include; to respond quickly and effectively with a set of prepared SOP or on-site modifications; to monitor on-site developments, so as to respond to changing conditions; to learn from past experiences; to anticipate impeding disasters (Hollnagel and Fujita, 2013). Learning from past experience can lead to anticipating the un-expected future events. Anticipation provides the preparedness to effective response during a crisis. In anticipation of this imminent threat, nations along the pacific ring of fire should be prepared in advance. For Malaysia, several keystone steps have been put in place, notably the establishment of the national Tsunami early warning system based in MetMalaysia. Tsunami simulation capability has been beefed up too.

MATERIALS AND METHODS

NLSWE and moving boundary: Linear shallow water equations are normally used to model the propagation of Tsunami waves in deep sea region with good accuracy. However, as a Tsunami wave approaches a coastal region where the water depth is shallow, the wavelength is shortened and the celerity is reduced, resulting in increases in the wave heights of the Tsunami. Hence, in shallow coastal region the linear shallow water equations are no longer adequate in for modeling such hydrodynamics. The advection and seabed friction must be carefully incorporated with decreased water depth. Therefore, a Non-Linear Shallow Water Equations (NLSWE) including advection and a bottom friction term are required to model such Tsunami behavior in shallow coastal region. The continuity and momentum equations of two-dimensional NLSWE are described as follows:

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

$$\begin{aligned}&\frac{\partial U}{\partial t}+\frac{\partial}{\partial x}\left(\frac{U^2}{H}\right)+\frac{\partial}{\partial y}\left(\frac{UV}{H}\right)+\\&gH\frac{\partial \eta}{\partial x}+\frac{gn^2}{H^{7/3}}U\sqrt{U^2+V^2}=0\end{aligned} \tag{2}$$

$$\begin{aligned}&\frac{\partial V}{\partial t}+\frac{\partial}{\partial x}\left(\frac{UV}{H}\right)+\frac{\partial}{\partial y}\left(\frac{V^2}{H}\right)+\\&gH\frac{\partial \eta}{\partial y}+\frac{gn^2}{H^{7/3}}V\sqrt{U^2+V^2}=0\end{aligned} \tag{3}$$

Where:

η(m) = The free surface displacement measured from a fixed datum (mean sea level)

d (m) = The water depth below the fixed datum

H (m) = η+d = The total water depth, g (m/sec^2) is the gravitational acceleration (m/sec^2)

n (sec/m$^{1/3}$) = The manning's relative roughness coefficient

U (m^2/sec) and V (m^2/sec) = The discharged fluxes in the x and y directions, respectively

The governing equations are solved using the explicit leap-frog finite difference scheme with an upwind algorithm for the nonlinear advection. However, the discretization of NLSWE is not adequate to model the run-up dynamics of Tsunamis along the beaches as the total water depth H must be properly computed between the interface of wet cells and dry cells. Therefore, a moving boundary algorithm is necessary to allow the discretized NLSWE to be computed over the entire computational domain. The details of moving boundary algorithm employed in TUNA-RP are available elsewhere (Jonientz *et al*., 2005).

RESULTS AND DISCUSSION

It is commonly reported that the sea level at Langkawi abruptly receded into the sea by distances exceeding 100 m before the arrival of the first Tsunami waves. This implies that the Tsunami waves were leading depression N-waves. The first elevation wave was followed by two additional waves in close succession, where the second wave was the biggest and the most destructive. Along the shore, run-up wave heights were observed to vary between 2 and 4 m with current speeds reaching or exceeding 12 m/sec. These magnitude of wave heights and current speeds can create wild turbulence to cause drowning or debris flows leading to death.

Figure 1 shows TUNA simulated Tsunami wave propagation beginning from the source at the Nicobar (the first snapshot), arriving at Langkawi offshore with depth of 50 m (4th snapshot) in about 3.5 h. This simulated arrival time tallies with the recorded arrival time of 3 h and 40 min. The simulated wave height at this offshore location was a = 1.2 m. The first snapshot is the initial Tsunami waves created by the abrupt uplifting of the sea floor by the earthquake. The subsequent three snapshots illustrate the wave propagation at intervals of 70 min. Figure 2 shows the bathymetry and topography of the TUNA-RP simulation domain for Langkawi with computational grid size of 10 m. The Tsunami waves propagate from the offshore location towards Langkawi

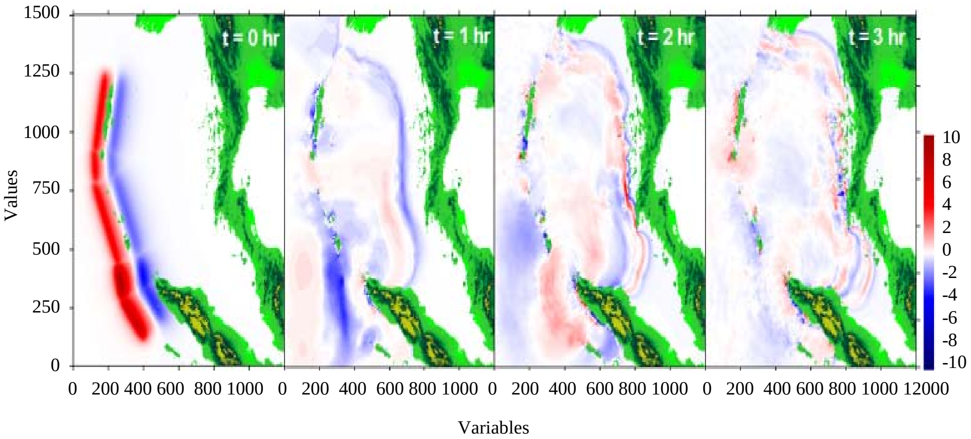

Fig. 1: TUNA-ME simulated wave propagation of the 2004 Andaman Tsunami towards NorthWest Peninsular Malaysia, arriving at Langkawi in 3 h 40 min

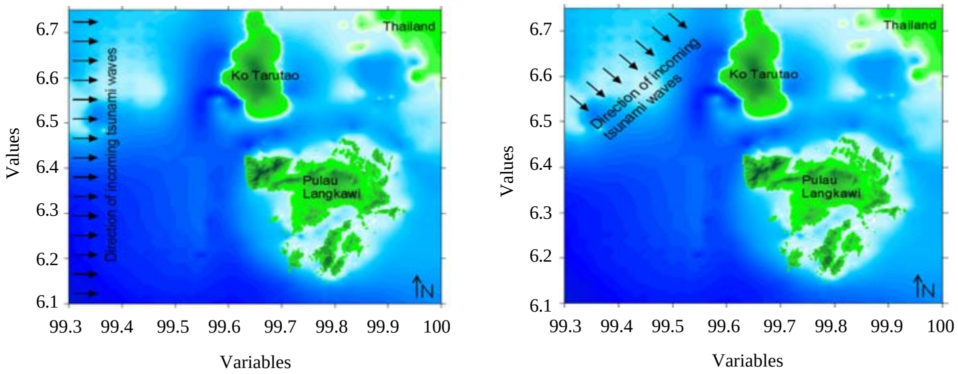

Fig. 2: Bathymetry and topography of the simulation domain in Langkawi with Tsunami waves propagating from the West (left) and from the NorthWest (right)

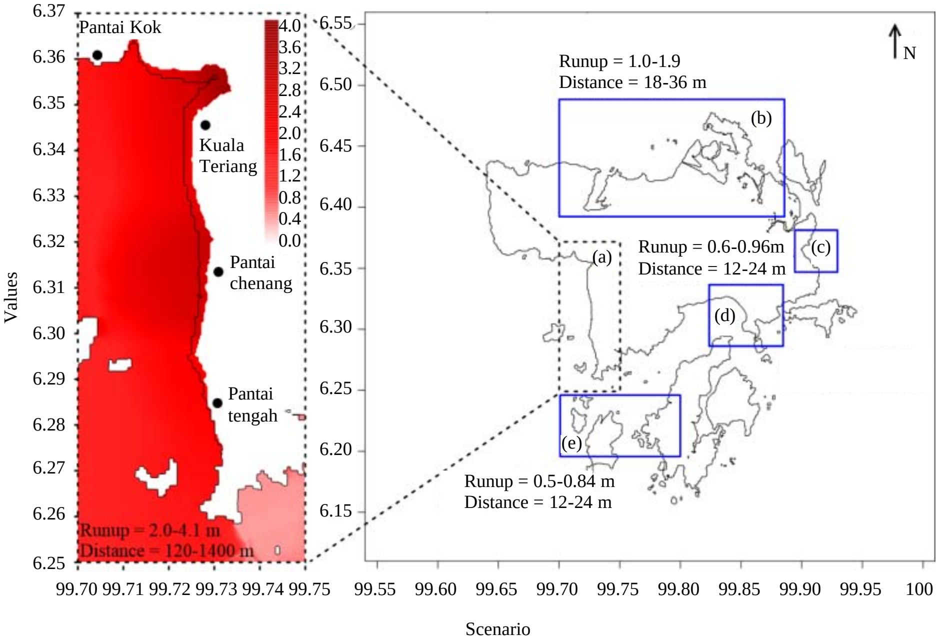

Fig. 3: Range of simulated run-up heights and inundation distances in five selected areas for Scenario 1

Table 1: Surveyed (Koh *et al*., 2009; National Centers for Environmental Information (NCEI) of (NOAA) and simulated run-up heights R and inundation distances D at six selected beaches in Pulau Langkawi for Scenario 1

			Surveyed (2004 Tsunami)		TUNA simulated	
Locations	Lat. (°N)	Long. (°N)	R	D	R	D
Pantai Tengah	6.25	99.72	3.66	44.5	2.25	45.0
Pantai Chenang	6.28	99.72	3.75	54.7	3.13	60.0
Pantai Kok	6.35	99.66	2.25	50.8	1.28	46.0
Pantai Kok	6.35	99.67	2.98	34.9	1.35	32.0
Kuala Teriang	6.35	99.70	3.09	27.0	2.42	34.0
Kuala Teriang	6.36	99.71	3.30	-	2.97	140.0

beaches from two directions, i.e., from the West (left) and from the NorthWest (right). The incident wave direction depends on the orientation of the Tsunami source generated by earthquake at the Andaman Sea North of Aceh. These two incident directs result in two scenarios of inundations denoted by Scenarios 3.1 and 3.2, respectively. The incident offshore Tsunami waves that run-up the Langkawi beaches used in this study takes the form of a solitary wave represented by the Gaussian hump $(x, y) = ae_{-(x^2/2\sigma^2_x + y^2/2\sigma^2_y)}$. Based upon simulation of the 2004 Tsunami propagation by TUNA-ME (Koh *et al*., 2009) this incident Tsunami at the offshore deep water region with depth of 50 m has amplitude a = 1.2 m with standard deviation σ = 5000 m (equivalent to 20 km in wavelength, ~4σ).

Scenario 1 Tsunami from the West, a = 1.2 m: In Scenario 1, the incident Tsunami waves propagate from the West with wave amplitude of a = 1.2 m at offshore depth of 50 m. The map for simulated run-up wave heights R and inundation distances D for area (a) is presented in shades of red in Fig. 3 (left). Similar maps for areas (b-e) are not shown due to space constraints. Instead, the ranges of simulated run-up heights R and inundation distances D at these four selected areas are summarized in Fig. 3 (right). The simulated run-up heights R and inundation distances D at six selected location in Area (a) are presented in Table 1. As may be seen from Table 1, the simulated run-up heights R and inundation distances D match the 2004 survey results (Koh *et al*., 2009) reasonably well, except at two locations, i.e., Pantai Kok. At these two spots, the simulated run-up heights are only half of surveyed values. The apparent discrepancy arises because the survey run-up wave heights at Pantai Kok were the observed results based upon measurements of highest water marks deposited on cliffy surface. When the Tsunami waves reached the cliff, the waves splashed upwards towards the sky, causing the water marks on the cliff to go further up the cliffs from the real run-up heights. This splashing of water waves on cliffs is not a major concern for inundation simulation models designed for wave run-up on mildly-sloped beaches and hence is not accounted for in TUNA-RP. This is the source of the discrepancy.

Scenario 2 Tsunami from the North West, a = 2.4 m: The Tsunami that devastated Fukushima resulting in the rare triple disasters on 11 March, 2011 prompted a critical scientific review of potential scenarios for future Tsunamis along the Pacific Ring of Fire. The general view is now more aligned towards an upward revision of earthquake strengths together with the subsequent

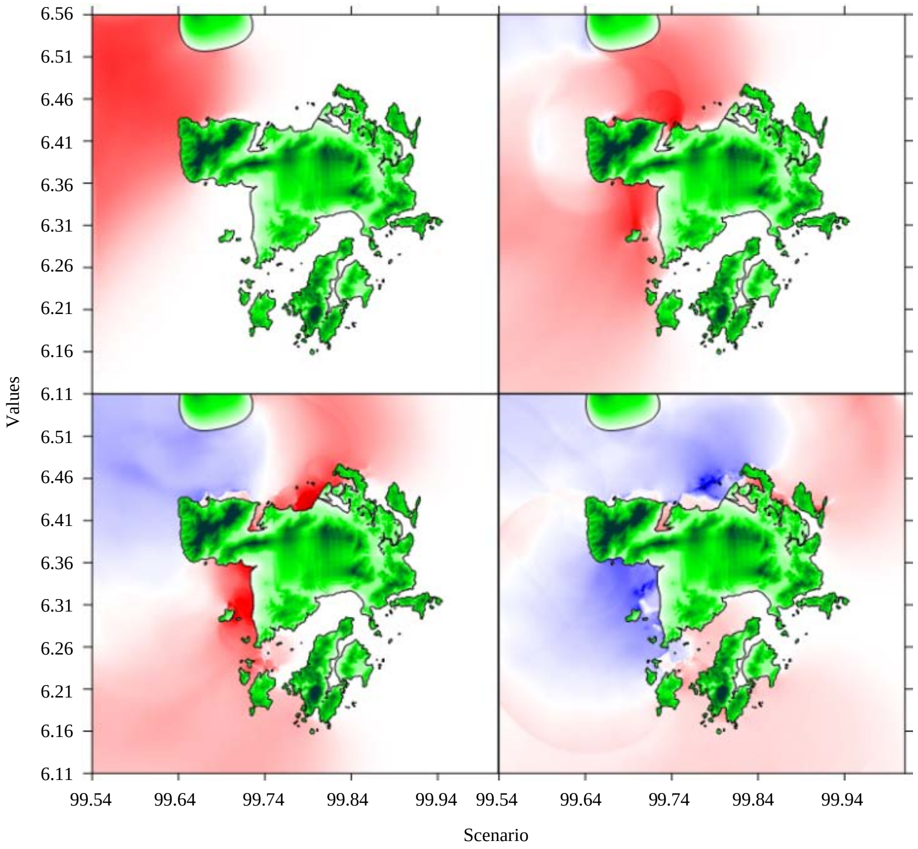

Fig. 4: Scenario 2 TUNA-RP simulation snapshots

Tsunamis that the earthquakes trigger. The earthquake zones around the Nicobar and Aceh areas remain active, ready to erupt at any moment with more vengeance, according to scientific consensus. To reflect this revised scientific view on earthquake strengths, the study accordingly adopts an upward revision of the earthquake strengths in the region. This upward revision of earthquake strength leads to an upward revision of potential Tsunami hazards in Langkawi. In this Scenario 2, the incoming waves have amplitude of 2.4 m at offshore depth of 50 m. The waves propagate towards the Southeast because of the Southwest-Northeast orientation of the earthquake rupture belts (Koh *et al*., 2009). Figure 4 red denotes positive elevation waves while blue indicates negative depression wave. The intensity of colour reflects the relative wave heights with more intense colour indicating higher wave heights. The waves inundate Pantai Kok (shaded red) at the NorthWest corner of Langkawi as shown in top left of Fig. 4. It should be noted that the beaches around Pantai Kok have generally cliffy shores with high slopes. Beaches with high slopes will have reduced run-up heights and shorter inundation distances. Hence, the incoming waves at Pantai Kok generate smaller run-up heights and shorter inundation distances because of its steeper slopes. The waves subsequently propagate in alongshore directions to inundate areas (a and b) (shaded in red) as shown in top right of Fig. 4. At this point in time, the waves at Pantai Kok begin to draw back to the mean sea level (shaded white), preparing to draw back further into the ocean. Soon after, parts of the waves propagate in the onshore direction, thereby severely inundating the low-lying terrains in area (a) as shown in Fig. 4 bottom left. Pantai Chenang and Kuala Teriang receive wave heights of between 4.12 and 5.27 m (Table 2), levels that pose severe danger to human lives. Some low-lying sections of area are also severely inundated with wave

Table 2: Surveyed (Koh *et al*., 2009; National Centers for Environmental Information (NCEI) of (NOAA)) and simulated run-up heights R and inundation distances D at six selected beaches in Pulau Langkawi for Scenario 2

			Surveyed (2004 Tsunami)		TUNA simulated	
Location	Lat (°N)	Long (°N)	R	D	R	D
Pantai Tengah	6.25	99.72	3.66	44.5	3.39	95.0
Pantai Chenang	6.28	99.72	3.75	54.7	4.74	135.0
Pantai Kok	6.35	99.66	2.25	50.8	2.34	60.0
Pantai Kok	6.35	99.67	2.98	34.9	3.26	55.0
Kuala Teriang	6.35	99.70	3.09	27.0	4.12	90.0
Kuala Teriang	6.36	99.71	3.30	-	5.27	375.0

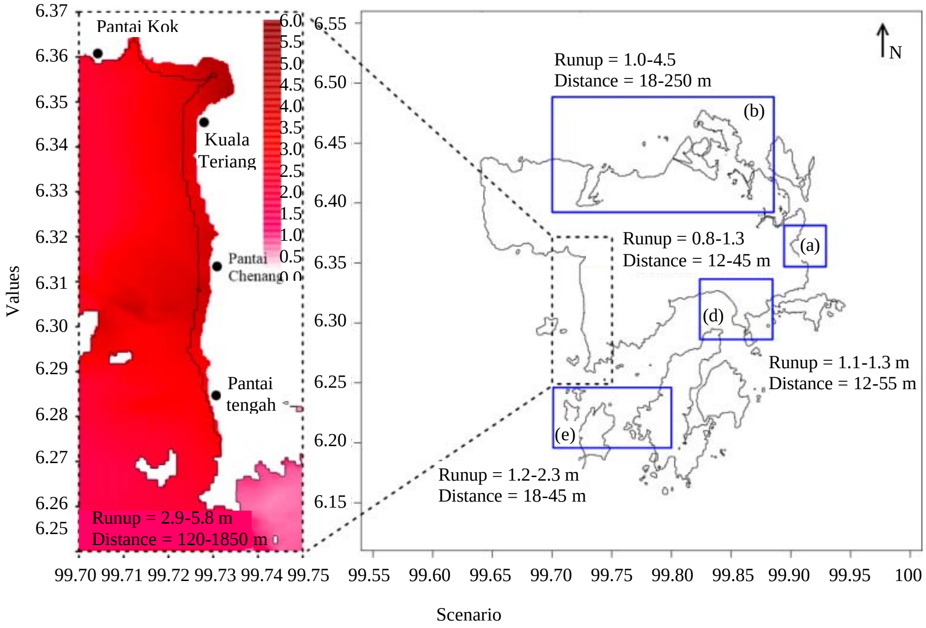

Fig. 5: Range of simulated run-up heights and inundation distances in five selected areas for Scenario 2

heights reaching 4.5 m (Fig. 5b). Being lower than sea level, the channels in area (b) are also badly inundated. Simultaneously, the waves now have already inundated area (e) with wave heights in the range of 1.2-2.3 m (Fig. 5e) while the waves at Pantai Kok have drawn back significantly into the ocean (shaded blue) as may be seen in Fig. 4 (bottom left). After inundating areas (a) and (b), the waves continue to propagate further into area (c) and into area (d), via Selat Kuah, inundating the low-lying terrains (Fig. 4, bottom right) with wave heights of up to 1.3 m (Fig. 5c and d). By now, the waves at areas (a and b) have drawn back deep into the ocean (shaded blue) while the propagating waves wrap around the East and South East of the Langkawi Island (shaded in light red).

The simulated run-up wave heights R and inundation distances D for Scenario 2 in area (a) is shown in Fig. 5 (left). The ranges of simulated run-up heights R and inundation distances D at four selected areas (b-e) in Langkawi are shown in Fig. 5 (right). The simulated run-up heights R and inundation distances D at six selected location in area (a) are presented in Table 2. As may be seen from Table 2, the simulated run-up heights R and inundation distances D are generally higher than the survey results recorded for the 2004 Tsunami, due to the upward revision of earthquake strength.

Tsunami hazards mitigation: The extensive and devastation damage inflicted by the 26 December, 2004 Tsunami is indeed a wake-up call for many living in the affected areas. Good lessons can be learned from past Tsunami experiences especially in the US for reducing the adverse impacts of Tsunamis. Tsunami education activities, materials and programs are recognized by the US NTHMP as the essential tool for Tsunami hazards mitigation (Dengler, 2005). All five Pacific States held workshops and forums to develop and disseminate education information to the public. In Malaysia, a series of workshops and seminars on warning systems, Tsunami modeling and education were held, since 2005 to assess Tsunami hazards mitigation programs and to define mitigation needs. In particular, a series of South China Sea Tsunami Workshops (SCSTW) has been held to develop capacity in a broad area of Tsunami hazards mitigation. The SCSTW were held in Taipei, Shanghai, Penang, Banda Aceh, Beijing and Singapore. Following the success of SCSTW in 2007 and 2008, a consensus was reached to appoint the first two researchers of this study to organize SCSTW3 in Universiti Sains Malaysia (USM) from 3-5 November 2009. This Tsunami workshop received contributions from Cornell University USA and Syiah Kuala University Indonesia as well as from other universities that participated in past SCSTWs. Other co-organizers and sponsors include the Malaysian Meteorological Department, Academy of Sciences Malaysia, Malaysian National Oceanography Directorate and Mercy Malaysia. The >150 participants from 30 nations attended the workshop including scientists from USGS, Academia Sinica Taipei, Tohoku University

International Research Institute of Disaster Sciences and the Philippines Institute of Volcanology and Seismology. The workshop focused on two themes: scientific, computational and engineering aspects of Tsunami hazards mitigation and social-cultural-economic implications and dimensions. Selected studies were published in two volumes of proceedings subsequent to the workshop (Koh *et al*., 2011) to provide assistance to those involved in developing Tsunami hazards mitigation programs anywhere in the world as a compliment to the US NTHMP efforts. The workshop primary goal is the development of Tsunami resilient communities by collaboration among various interested stake-holders worldwide, drawing insights and inspirations from each other. This goal is achievable via three procedures: review current Tsunami scientific and engineering research, review existing Tsunami early warning systems and implement plans for sustained Tsunami hazards mitigation programs in the South China Sea Region. Education is identified as the primary tool for reducing human casualties during a Tsunami. To save human lives, the workshop identified three principal education needs of communities in hazardous zones as follows: recognizing the signs of an impending Tsunami; understanding what areas are at risk and knowing how and when to evacuate. Of significant importance is that evacuation signage should be posted to serve an essential educational role by raising community awareness before a Tsunami and by notifying people of appropriate evacuation routes to follow during a Tsunami. Meetings with community associated with the development and release of evacuation maps should be held to allow community members to make decisions on the locations of evacuation routes and to get feedback from Tsunami experts. These goals and procedures are inspired by and are broadly in line with similar findings and concepts developed during the US NTHMP (Eisner, 2005; Bernard, 2005) that proceeded the SCSTWs.

The 1946 Aleutian Tsunami destroyed much of Hilo, Hawai'i. Since then a network of sirens has been established to provide an early public alert of impeding Tsunamis. Studies in the 1960s, however, showed that understanding of the meaning of siren soundings was indeed very low. The ambiguity in understanding had resulted in much fatalities in the 1960 Chilean Tsunami that again destroyed much of Hilo. The Hawaiian public has since been exposed to monthly tests of the sirens and descriptions of the system have been widely published in telephone books. Yet, understanding of the meaning of the siren remains disturbingly low at 13% (Gregg *et al*., 2007). A major change is needed in Tsunami education, even in Hawai'i to increase public understanding of and effective response to both official alerts and natural warning signs of impeding Tsunamis. Five sirens have been installed in Penang with additional two in Langkawi. To what extent do the local communities understand the siren soundings remains unknown and hence need to be addressed.

The Malaysian Tsunami hazards mitigation program should address three major components: hazard assessment, warning guidance and hazards mitigation, following NTHMP guidelines. Hazard assessment and warning guidance are led by physical scientists (NOAA, USGS in USA; MetMalaysia, USM in Malaysia) who, using research and modeling methods, develop products that allow communities to identify their Tsunami hazard areas and receive more accurate and timely warning information. Tsunami hazards mitigation should be led by the emergency managers (FEMA in USA; NSC in Malaysia) who use their experience and networks to translate science and technology into user-friendly planning and education products. Mitigation activities should focus on assisting federal, state and local officials who must plan for and respond to disasters and for the public that is deeply affected by the impacts of both the disaster and the pre-event planning efforts.

CONCLUSION

This study has presented the development and verification of an in-house Tsunami run-up simulation numerical software code-named TUNA-RP. TUNA-RP is then used to simulate two potential scenarios of Tsunami run-up along beaches in Langkawi Island of Malaysia, due to earthquakes originating from the Andaman Sea. A comparison is made between measured Tsunami wave heights and inundation distances for the 2004 Andaman Tsunami and TUNA-RP simulated values to demonstrate the capability of TUNA-RP. Potential Tsunami run-up scenarios indicate that several hotspots in Langkawi may receive run-up wave heights reaching or exceeding 5 m. Hence the study articulates the urgent needs to develop Tsunami resilience among affected coastal communities by the implementation of a Tsunami hazards mitigation program suitable for Langkawi. The achievements of the US National Tsunami Hazards Mitigation Program are highlighted to serve as a spring board and benchmark. It is hoped that the Tsunami hazards mitigation program for Langkawi and Penang will be implemented in the near future. Towards this goal, research grants will be sought to implement this program.

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