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ORIGINAL PAPER

A 3-tier tsunami vulnerability assessment technique for the north-west coast of Peninsular Malaysia

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Abstract The 2004 tsunami that struck the Sumatra coast gave a warning sign to Malaysia that it is no longer regarded as safe from a future tsunami attack. Since the event, the Malaysian Government has formulated its plan of action by developing an integrated tsunami vulnerability assessment technique to determine the vulnerability levels of each sector along the 520-km-long coastline of the north-west coast of Peninsular Malaysia. The scope of assessment is focused on the vulnerability of the physical characteristics of the coastal area, and the vulnerability of the built environment in the area that includes building structures and infrastructures. The assessment was conducted in three distinct stages which stretched across from a macro-scale assessment to several local-scale and finally a micro-scale assessment. On a macro-scale assessment, Tsunami Impact Classification Maps were constructed based on the results of the tsunami propagation modelling of the various tsunami source scenarios. At this stage, highly impacted areas were selected for an assessment of the local hazards in the form of local flood maps based on the inundation modelling output. Tsunami heights and flood depths obtained from these maps were then used to produce the Tsunami Physical Vulnerability Index (PVI) maps. These maps recognize sectors within the selected areas that are highly vulnerable to a maximum tsunami run-up and flood event. The final stage is the development of the Structural Vulnerability Index (SVI) maps, which may qualitatively and quantitatively capture the physical and economic resources that are in the tsunami inundation zone during the worst-case scenario event. The results of the assessment in the form of GIS-based Tsunami-prone Vulnerability Index (PVI and SVI) maps are able to differentiate between the various levels of vulnerability, based on the tsunami height and inundation, the various levels of impact severity towards existing building structures, property and land use, and also indicate the resources and human settlements within the study area. Most importantly, the maps could help planners to establish a zoning scheme for potential coastline development

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based on its sensitivity to tsunami. As a result, some recommendations on evacuation routes and tsunami shelters in the potentially affected areas were also proposed to the Government as a tool for relief agencies to plan for safe evacuation.

Keywords Tsunami vulnerability assessment · Physical Vulnerability Index · Structural Vulnerability Index · GIS

1 Introduction

Previously perceived as safe from tsunami hazards, the coastal region of Malaysia is now no longer considered to be in the “comfort” zone (Abdullah et al. 2005). When the December 2004 Indian Ocean Tsunami occurred, Malaysia was not spared by the tsunami generated by these gigantic waves. Although sheltered from the high-wave environment of the Indian Ocean by Sumatra, these waves penetrated into the northern half of the Straits of Malacca causing the death of 68 people and damage and loss of properties along the north-west coast of Peninsular Malaysia. The states of Kedah, including the island of Langkawi, and Pulau Pinang experienced the worst damage, whilst the tidal turbulence extended to about 300 km south into the Straits of Malacca.

Thus, Malaysia is not spared from the agony of any future tsunami. Instead, the western coastline of Peninsular Malaysia can now be regarded to face a certain degree of risk from tsunami wave propagation originating from the Sumatra waters. As a result, the Malaysian government, through the Department of Irrigation and Drainage Malaysia (DID), has formulated its plan of action in disaster mitigation strategies and coastal development planning. It is essential that for future planning and development of the coastal area, urban and regional planners need to know which parts of the coastline are more vulnerable to tsunami impact and which are not so vulnerable. Hence, a tsunami vulnerability assessment (TVA) was carried out to determine the vulnerability levels of each sector along the 520-km-long coastline towards a future worst-case scenario tsunami event.

1.1 The study area

The study area is located in the Straits of Malacca which is bounded by Andaman Sea in the north and Singapore Straits in the south. It is also shielded from the Indian Ocean by Sumatra in the west. The area of interest extends along the north-west coast of Peninsular Malaysia, which includes the four states namely Perlis, Kedah (including Langkawi), Penang and north Perak. It covers a coastal length of more than 500 km and is bounded by the four end coordinates of 3.75°N 99.79°E, 4.23°N 100.94°E, 6.69°N 100.16°E and 28°N 98.95°E (see Fig. 1).

The coastline of the study area is further divided into 52 grid cells of 10 km length and 2 km width each. Parameters that are pertinent to tsunami impacts such as the coastal landform, geologic materials, coastal slope and general land use of each cell were then determined to describe its physical characteristics. These parameters are also used as the fundamental physical variables in the computation of the Physical Vulnerability Index. A detailed description of the study area is provided in Ismail et al. (2010).

The offshore and nearshore bathymetries extracted from Malaysian Nautical Chart No. MAL5 were digitized and superimposed together with the coastal hydrographic survey data obtained from various government departments to provide the bathymetry of the study area

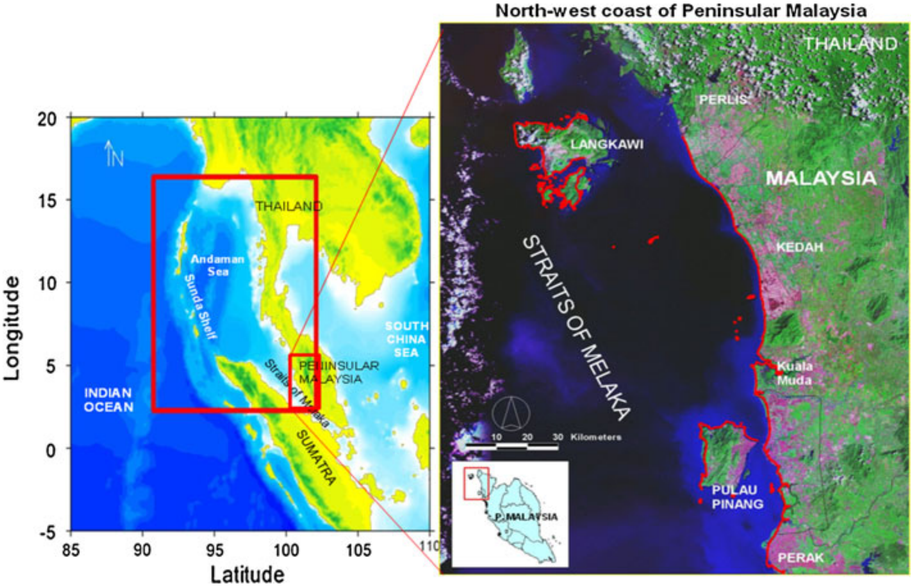


Fig. 1 Location of the study area in relation to Andaman Sea and Sunda Shelf (**a**). The inset in the (**b**) shows the map of Peninsular Malaysia

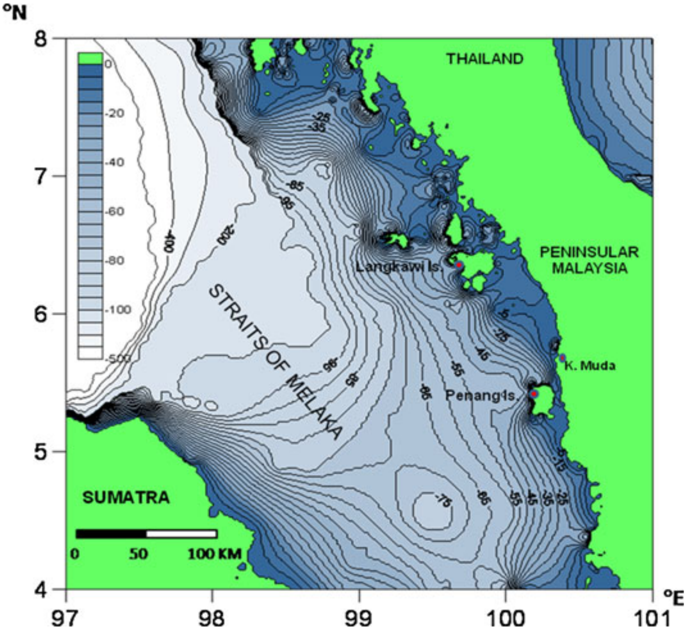


Fig. 2 Offshore and nearshore bathymetry of the study area

as shown in Fig. 2. It is generally observed that the north-west coast of Peninsular Malaysia has a 5 m shallow water depth extending across about 40 km off Langkawi Island and about 15 km off Penang Island. However, the southern part of Penang Island has a short stretch of shallow water area. The sea bed gradually increases to about −50 m at approximately 30–50 km off the whole coastline.

1.2 Objectives and scope of study

The ultimate goal of the study was to develop a GIS-based classification map of areas along the north-west coast of Peninsular Malaysia that are vulnerable to future tsunami impacts, based on scenario-generated tsunamis in the northern part of the Straits of Melaka and its connecting water bodies. As stipulated in the Terms of Reference and in order to meet the objectives of the study, the scope of the work has been organized into several study components as outlined below:

(i) To conduct tsunami hazard assessment involving geological and palaeo-tsunami studies, tsunami modelling and inundation modelling. A more specific investigation on the tsunami propagation and run-up processes in the northern part of the Straits of Melaka was carried out by developing our own Tsunami Predictive Model as a tool to predict, identify, evaluate and map the potential vulnerable areas to future tsunami attacks.
(ii) To perform a tsunami vulnerability assessment and GIS mapping in order to produce tsunami impact maps based on predicted nearshore heights, inundation depths and inland penetration limits, for the worst-case scenario for planning and zoning purposes.

In this paper, the authors intend to present and discuss only the second scope of the work although a brief description of the former is also highlighted in order to enlighten the approach used prior to presenting the vulnerability assessment technique applied in this study. It is therefore intended to describe the integrated methodology developed in this study, which constitutes three levels of assessment in order to determine the various degrees of vulnerability as well as to narrow down the vulnerability assessment specific to the potentially highly impacted areas as much as possible.

1.3 TVA literature

The term “vulnerability” and its application have many different connotations in hazard literature and vary when referring to different disasters (Cutter 1996, 2001; Cutter et al. 2003; Weichselgartner 2001; Wisner et al. 2004). In the case of a tsunami, a widely accepted definition is given in UNESCO-IOC Guidelines (UNESCO 2009). It covers social, physical, environmental and economical aspects of vulnerability due to tsunami impact. However, the scope of assessment in this study is focused on the vulnerability of the physical characteristics of the coastal area, and the vulnerability of the built environment in the area concerned including building structures and infrastructures.

By examining previous tsunami risk maps and literatures, Papathoma et al. (2003) observed that most of the earlier work had assumed that tsunami vulnerability was uniform but recent researches demonstrate that it should be dynamic. Recent works (Papathoma and Dominey-Howes 2003; Dominey-Howes and Papathoma 2007; Dall’Osso et al. 2009a, b and Kaplan et al. 2009) demonstrated that a tsunami vulnerability analysis needs to be dynamic and that it should cover several variables to present a more realistic result of spatial and temporal pattern of vulnerability.

In recent years, several models and methodologies have been developed to evaluate tsunami vulnerability. “Papathoma Tsunami Vulnerability Assessment (PTVA) Model” has been developed to assess building vulnerability due to tsunami (Papathoma et al. 2003). It has been validated using the data collected after 2004 Indian Ocean tsunami (Dominey-Howes and Papathoma 2007) and has been applied and tested in the United States (Dominey-Howes et al. 2010). A revised version of the PTVA model, known as PTVA-3, has been developed by Dall'Osso et al. (2009a, b) whilst validated and tested at Aeolian Island, Italy (Dall'Osso et al. 2010). Liu et al. (2007) devised a method called "Probabilistic Forecast of Tsunami Hazard" that determines the probability distribution of tsunami waves excited by a hypothetical earthquake. Nunes et al. (2009) analysed tsunami vulnerability due to impact of tsunami with defined tsunami wave height and sea level scenarios.

2 Methodology

The tsunami vulnerability assessment was conducted in three distinct stages which later culminated into several Tsunami Vulnerability Index maps of various scales, as illustrated in Fig. 3:

(i) a macro-scale Tsunami Impact Classification Map for the north-west coast of Peninsular Malaysia for the various tsunami source scenarios;
(ii) a local-scale Physical Vulnerability Index (PVI) map for the physical vulnerability level of the highly impacted areas obtained from (i) above; and

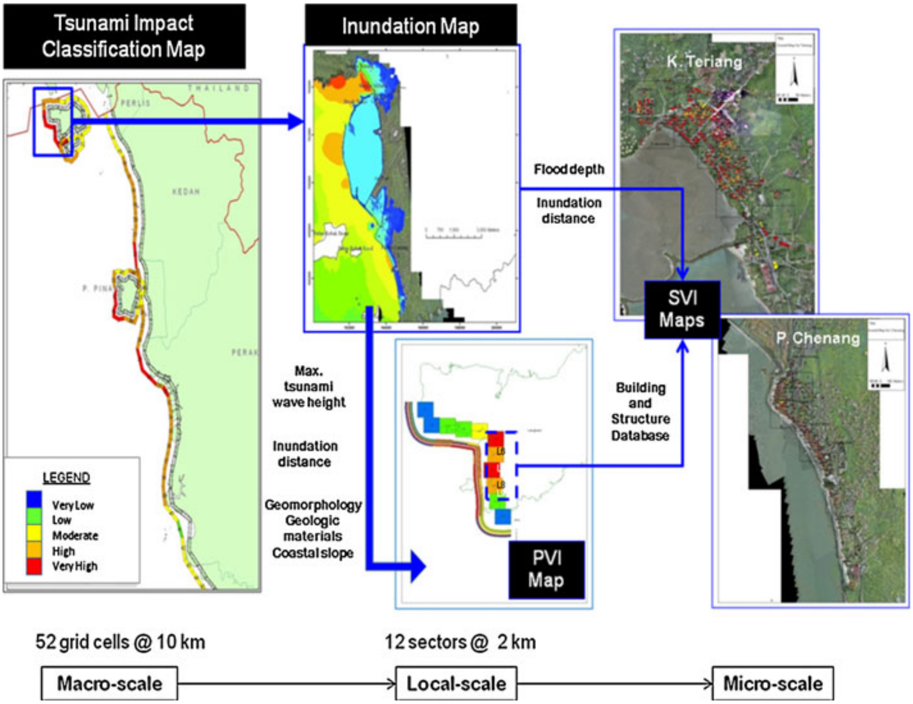


Fig. 3 The flow of the TVA methodology used in determining the Tsunami Vulnerability Index at various scales of assessment

(iii) a micro-scale Structural Vulnerability Index (SVI) map for the vulnerability level of the built environment (buildings and structures) within the highly indexed PVI areas indicated by (ii) above during the worst-case tsunami scenario.

On a macro-scale assessment, Tsunami Impact Classification Maps were constructed based on the results of the tsunami propagation modelling of the various tsunami source scenarios. At this stage, highly impacted areas were selected for the next stage of assessment. This constitutes the local-scale assessment in the form of local flood maps derived from inundation modelling of the selected areas. Tsunami heights and inundation distance obtained from the flood maps were then used to produce the Tsunami Physical Vulnerability Index maps. These maps recognize sectors within the selected areas that are highly potential to a maximum tsunami run-up and flood event. This then led to the next final stage which is the development of Structural Vulnerability Index maps. These maps may qualitatively and quantitatively capture the physical and economic resources that are in the tsunami inundation zone during the simulated worst-case scenario event.

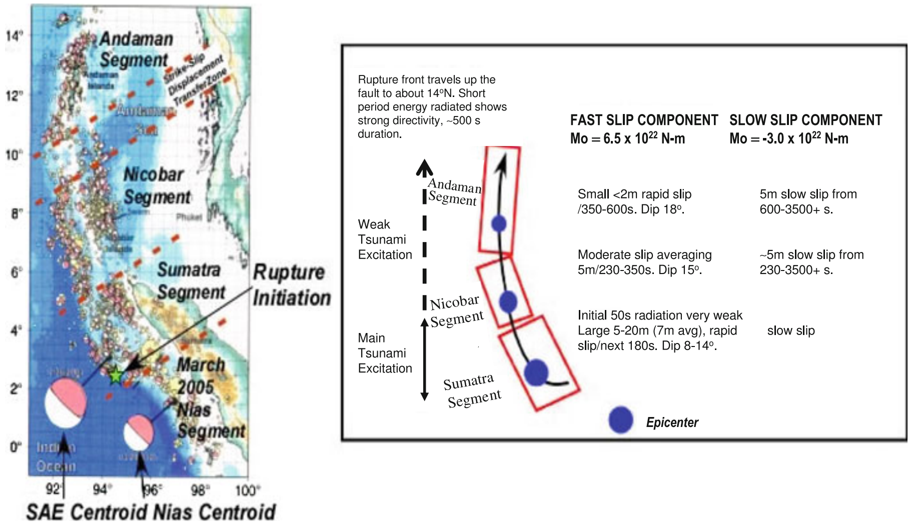
2.1 Tier 1: macro-scale assessment (scenario-based Tsunami Impact Classification Maps)

2.1.1 Tsunami source identification

Prior to measuring the vulnerability, understanding and quantifying the tsunami hazards are of primary importance. The former included identifying the dominant source regions and fault mechanisms after which computer modelling of the tsunami propagation into the Straits of Melaka was undertaken. Identification of geological records of historical tsunamis and written records of post-tsunami events within the study area revealed that the extreme tsunami generated in the Andaman segment in December 2004 involved both thrust and bookshelf faulting within the compacted sediments of the Andaman Sea segment of the Great Sunda Arc and large ocean floor displacements over a long rupture. Earthquakes with a magnitude of 8.0 or greater (such as the 1941 and 2004 events) were associated with “dip-slip” types of vertical crustal displacements along thrust faults and thus may have the potential of generating very destructive tsunamis in the entire Bay of Bengal Region, the Andaman Sea and the Indian Ocean. There were also reports of widespread uplift and subsidence in the Andaman Islands during the 2004 earthquakes, consistent with fault movement. The potential tsunami source areas that may affect Peninsular Malaysia lie along the Andaman Sea and Sumatran segments of the Sunda Arc (Andaman, Nicobar and Sumatran segments). These segments are capable of producing large, shallow tsunamigenic earthquakes with maximum Richter magnitudes of up to 8 (up to 9 or even more in Moment Magnitude if more than one segment breaks). Hence, based on the statistical and historical information obtained, the location of the tsunami sources and details of tsunami source parameters were identified by Ismail et al. (2010) and shown in Fig. 4 and Table 1, respectively.

2.1.2 Scenario-based tsunami modelling

In order to produce the Tsunami Impact Classification Map for the worst-case scenario, a scenario-based modelling approach has been adopted. Various scenarios regarding potential credible sources were simulated to analyse the possible impacts. These included a



SAE: December 26, 2004 Sumatra-Andaman Earhtquake (SAE) rupture segmentation

Fig. 4 Location of potential sources of tsunami in the Andaman Sea and NW Sumatra Offshore (The three rupture segmentation of the 2004 tsunami modified from Lay et al. 2005, http://www.hgs.org/en/art/708/)

Table 1 Fault parameters for propagation modelling

Model	Scenario 2004	Scenario 1 (Sumatra fault)	Scenario 2 (Nicobar fault)	Scenario 3 (Andaman fault)
Start point	N1°12′, E96°25′	N1°12′, E96°25′	N5°30′, E92°58′	N9°13′, E91°31′
End point	N13°58′, E92°13′	N5°30′, E92°58′	N9°13′, E91°31′	N13°58′, E92°13′
Fault length (km)	1,170	200	670	300
Fault width (km)	150	150	150	150
Strike angle (°)	350	335	350	360
Dip angle (°)	15	15	15	15
Slip angle (°)	90	90	90	90
Displacement (m)	20	20	20	20
Focal depth (km)	10	10	10	10

tsunami source similar to the 2004 tsunami event and an additional three other scenarios, with generation points in the proximity of the various faults as follows:

- Scenario Case 1: the Sumatra fault
- Scenario Case 2: the Nicobar fault
- Scenario Case 3: the Andaman fault

The tsunami source and propagation modelling was run using TUNA-M2 which is an in-house tsunami simulation model developed during the course of this study by a group of researchers from Universiti Sains Malaysia (Koh et al. 2009). In the tsunami source modelling, only tsunamis generated by submarine earthquakes were simulated. The focus was on the Sumatra–Andaman earthquake with a magnitude of 9.3 on the Richter scale that occurred in 26 December 2004. The initial tsunami wave generation was assumed to be formed by an initial surface deformation or the dip-slip fault mechanism. The simulated wave height time series at three selected observation locations agreed with eyewitness accounts, in terms of both arrival times and the shape of the waves in the form of leading depression N waves. The propagation of tsunami was simulated by the depth-averaged two-dimensional shallow water equations (SWE) as recommended by the Intergovernmental Oceanographic Commission (IOC 1997). Verification of results using sensitivity tests and simple checks was carried out by validating TUNA-M2 against other established models such as COMCOT and TUNAMI-N2 developed by Tohoku University (Imamura et al. 1988). Details regarding the COMCOT model can be referred to Liu et al. (1998). The verification and validation of the TUNA-M2 model was provided by Koh et al. (2009). The agreement between results simulated by TUNA-M2 and those simulated by COMCOT and TUNAMI-N2 at all observation points was very good, indicating proper performance of TUNA-M2.

2.1.3 Tsunami Impact Classification Map

Based on the computer modelling results obtained, the maximum tsunami level for the four tsunami scenarios along the north-west coast of Peninsular Malaysia was calculated. The results were then ranked according to the simulated tsunami wave height at the shoreline in which the ranking scale created was based on the widely used Imamura-Iida scale system (Bryant 2005) and Maldives ranking system (UNDP 2006) as presented in Table 2.

Using the Tsunami Index Ranking Scale shown in Table 2, each of the grid cells in the study area was evaluated and ranked accordingly. The scenario-based Tsunami Impact Classification Maps are shown in Fig. 5a–d from which the worst impact or the worst-case scenario affecting the north-west coast of Peninsular Malaysia was selected. It is observed that the worst-case scenario that may affect the Malaysian coastline in future has a source similar to the 2004 Indian Ocean Tsunami. In fact, it could cause even more severe damage if it were to happen during a high tide. Therefore, it was inferred that the worst-case scenario is a combination of the 2004 tsunami that could occur during the highest astronomical tide (HAT). The Tsunami Impact Classification Map for the worst-case scenario is depicted in Fig. 6.

2.2 Tier 2: local-scale assessment (development of the Tsunami Physical Vulnerability Index)

2.2.1 Inundation modelling

Based on the worst-case Tsunami Impact Classification Map (Fig. 6), the tsunami inundation modelling was carried out for the areas with very high impact ranking (more than 3-m tsunami level marked in red) and for high-density build-up areas. The selected areas are the west coast

Table 2 Ranking scale used for Tsunami Impact Classification Map for N–W coast of P. Malaysia

Variables	Very low 1	Low 2	Moderate 3	High 4	Very high 5
Maximum tsunami height (H)	$H \leq 0.5$ m	$0.5 < H \leq 1.0$ m	$1.0 < H \leq 2.0$ m	$2.0 < H \leq 3.0$ m	$H > 3.0$ m

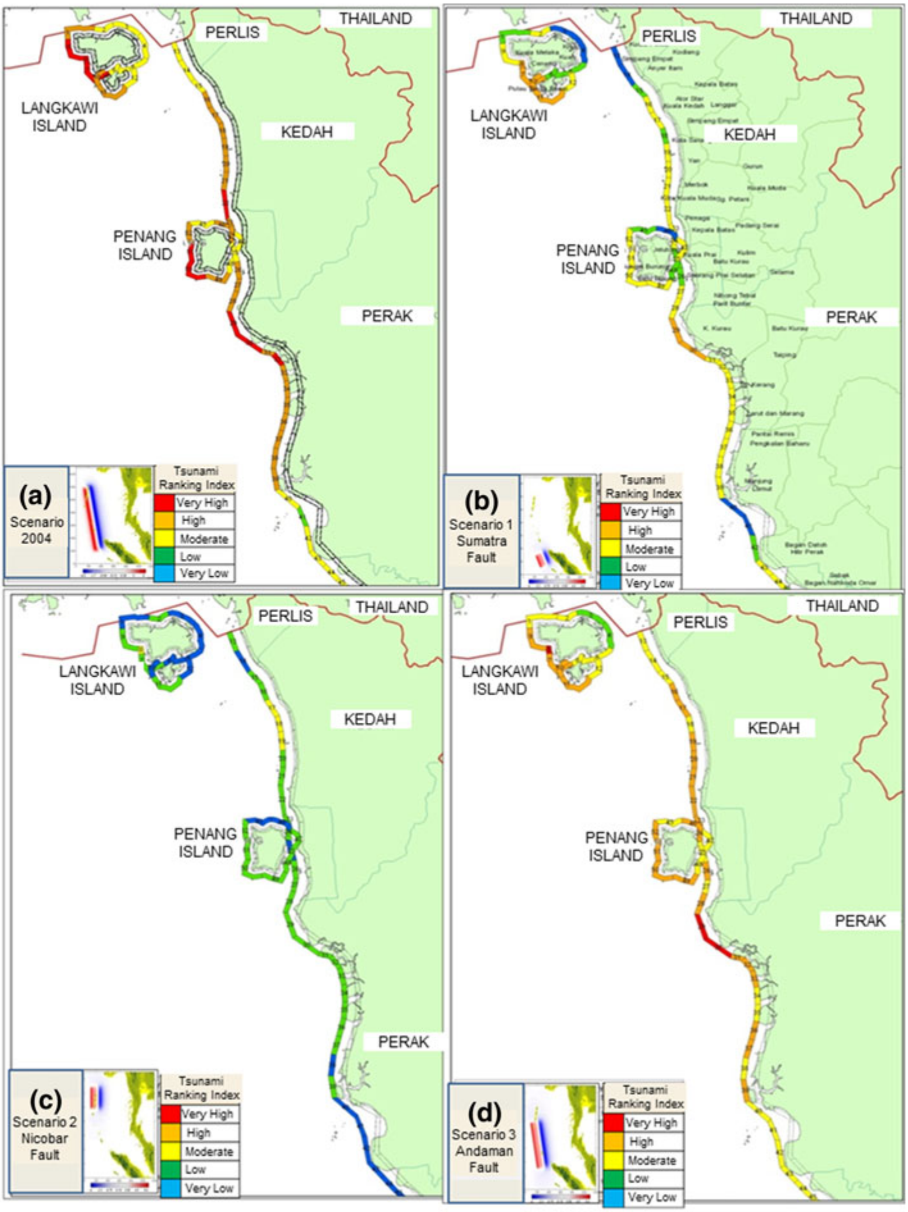


Fig. 5 Scenario-based Tsunami Impact Classification Maps for the N–W Coast of Peninsular Malaysia **a** 2004 Scenario, **b** Scenario 1: Sumatra Fault, **c** Scenario 2: Nicobar Fault, **d** Scenario 3: Andaman Fault

of Langkawi (Area 1), Kuala Muda (Area 2), the north and west coasts of Penang Island (Areas 3 and 4, respectively), as shown in the insets of Fig. 6. A 2-D hydrodynamic model, TELEMAC-2D, was then utilized for the inundation modelling in all the four selected areas. In this paper, only Area 1—Langkawi—is highlighted to illustrate the development of the Tsunami Vulnerability Index at the local and micro-scale stages of the assessment.

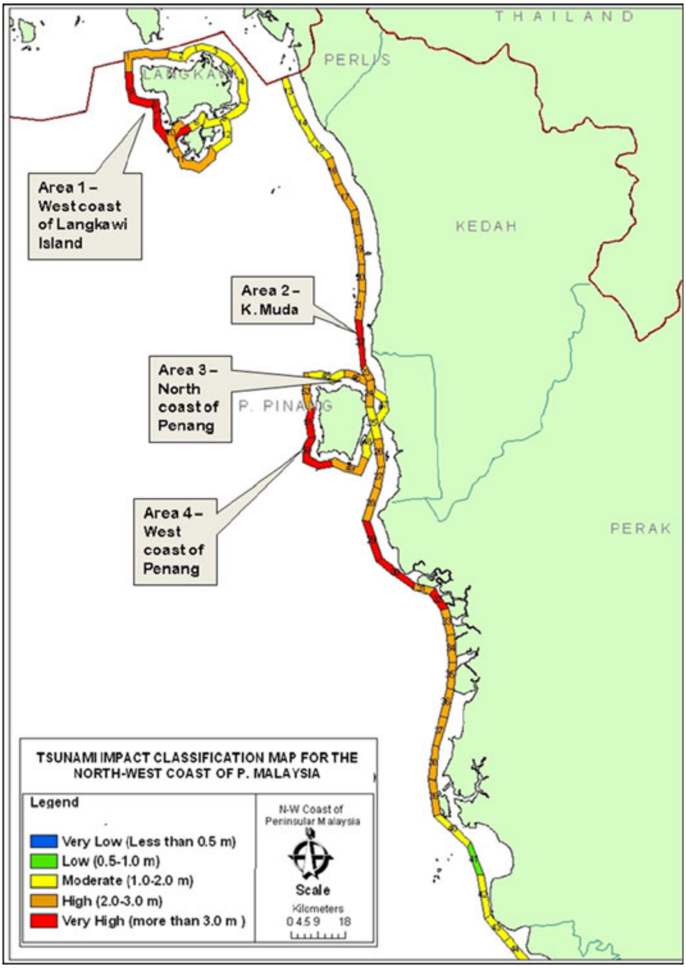


Fig. 6 Tsunami Impact Classification Map of the worst-case scenario showing the highly impacted areas for further modelling

TELEMAC is a 2-D hydrodynamic model developed by the National Hydraulics and Environment Laboratory (Laboratoire National d'Hydraulique et Environment—LNHE) of the Research and Development Directorate of the French Electricity Board (EDF-DRD). It is designed to simulate physical processes associated with rivers, estuaries, coastal and ocean waters based on the finite element technique and applied to unstructured triangular grids. Considering that the set-up of a hydrodynamic numerical model demands for a large spatial expansion of the model domain (covering the area until −50 m depth), and also a relatively high resolution of the topography and bathymetry, hence a great number of calculation nodes are required. Since TELEMAC-2D model works with unstructured triangular meshes, we can avoid unnecessary detailed computations where different regions can have different resolutions. This allowed the computational resources to be directed where they were most needed.

The inundation model for the west coast of Langkawi covers an area of about 15 km along the coastline, up to the +10 m land level area and −50 m seabed contour area. The triangular mesh was constructed with a 20-m resolution for the coastal area and a 2-km resolution at the offshore areas with a total of 120,014 nodes**.** The output from TUNA-M2 was used as input for the TELEMAC-2D model, and for calibration purposes, the initial water elevation was set at mean sea level. Results of the tsunami inundation modelling showed that the high-impact areas are around Pantai Chenang and Kuala Teriang, as portrayed in Fig. 7. The right panel in Fig. 7 indicates a general overview of the various sectors along the west coast of Langkawi, which would be susceptible to tsunami inundation. It is observed that sectors L5 to L10 would be affected by the tsunami flood waters in which sectors L6 and L8 would be inundated to a maximum distance of approximately 1.6 and 1.9 km, respectively. This condition is similar to those recorded during the tsunami on 26 December 2004.

2.2.2 Computation of the tsunami Physical Vulnerability Index (PVI)

After determining the flood map, a Coastal Vulnerability Index (CVI) methodology originally proposed by Gornitz (1990) has been adopted and then modified to assess the physical vulnerability of the coastal area to tsunami impact. The CVI method uses a Relative Vulnerability Index as an indicator to determine the level of vulnerability of a coast to changes as a result of a certain set of physical variables. It has been widely used to assess such vulnerability for sea level rise impacts for over a decade (Pendleton et al. 2010).

In this Tsunami Physical Vulnerability Index (PVI) assessment, the PVI is based on the CVI approach in which the physical parameters are defined as those geomorphologic characteristics along the coastline that may determine the current state of its vulnerability against the tsunami hazards (as opposed to sea level rise). It is therefore proposed that the following geomorphologic and tsunami hazard variables may reduce, increase or maintain the current state of the vulnerability of a coastline:

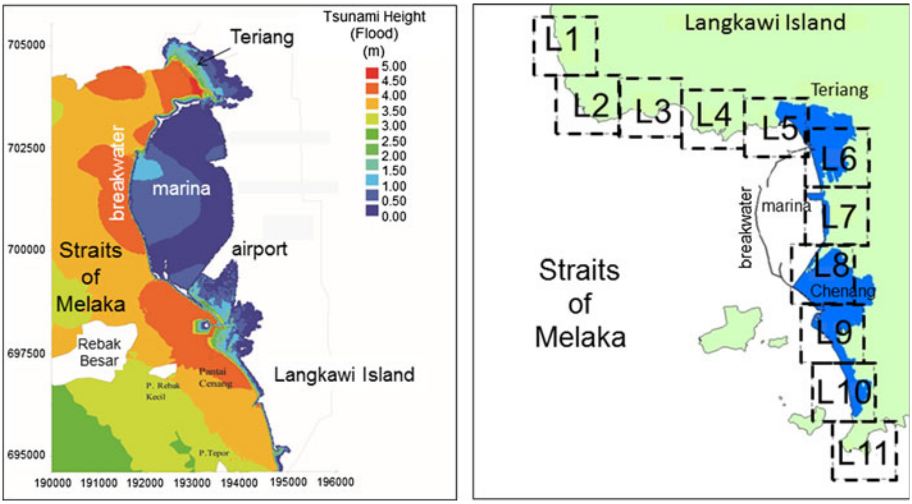


Fig. 7 Tsunami heights or flood depths for the 2004 tsunami scenario (**a**) and potential inundated areas in the various sectors along the west coast of Langkawi (**b**)

Geomorphologic state variables	Tsunami hazard variables
Geomorphology	Tsunami wave height (maximum water level)
Geologic materials	Inundation distance
Coastal slope	

The geophysical variables have been ranked using a scale from 1 (very low) to 5 (very high) using the USGS ranking system of Thieler and Hammer-Klose (1999), whilst the tsunami hazard variables adopted the modified Japanese and Maldives ranking systems as represented in Table 3.

The rankings for each variable were used in (Eq. 1) to calculate the Physical Vulnerability Index (PVI); the results then ranked using the same scale used to highlight the different vulnerability of the coastal area due to tsunami impact of a certain magnitude.

$$\mathrm{PVI} = \sqrt{\frac{(a \times b \times c \times d \times e)}{5}} \quad (1)$$

where,

a geomorphology
b geologic materials
c coastal slope
d tsunami wave height
e inundation distance

Table 3 Ranking of variables in determining the Tsunami Physical Vulnerability Index

Variable	Ranking				
	Very low 1	Low 2	Moderate 3	High 4	Very high 5
Geomorphology	Rocky cliff	Medium cliffs; indented coast	Low cliff; alluvial plains	Cobble beaches; estuary; lagoons	Barrier beaches; sand beaches; mud flats; deltas; mangrove
Geologic material	Old erosion resistant rocks and strong metamorphic rocks	Sedimentary rocks and weak metamorphic rocks	Unconsolidated sediments (loose, uncemented)	Recent volcanic materials	Coral reef
Coastal slope (%)	>1.2	1.2–0.9	0.9–0.6	0.6–0.3	<0.3
Tsunami wave height (m)	<0.5	0.5–1.0	1.0–2.0	2.0–3.0	>3.0
Inundation distance (m)	<50	50–100	100–200	200–300	>300

A brief description of these variables is provided as follows:

a. *Geomorphology:* The onshore coastal geomorphology is a key factor influencing the extent of inundation and run-up. It can present the relative erodibility of different land form types (Pendleton et al. 2006, 2010; Dwarakish et al. 2009).
b. *Geologic Material:* The geologic material making up the coastal land form may influence the degree of erosion and sedimentation. The incident tsunami wave and its subsequent seaward draining of floodwater can significantly erode sandy beaches (Dalrymple and Kriebel 2005).
c. *Coastal Slope:* Regional coastal slope and bathymetry of the area can influence the inundation distance and run-up wave height (Koh et al. 2009). Areas with gentle slope are suspected to inundate faster than areas with steep slope (Pendleton et al. 2004, 2010; Dwarakish et al. 2009).
d. *Tsunami Wave Height and Inundation Distance:* Tsunami wave height and inundation distance are probably the most dominant variables in the tsunami vulnerability assessment. A devastating tsunami wave (e.g. 10-m wave at Banda Aceh in 2004 tsunami) can easily wipe out almost everything in the area and inundate several kilometres inland.

The PVI assessment was then performed for the west coast of Langkawi to determine the degree of vulnerability of its coastline at the local level. The 11-km-long coastline is divided into 11 sectors (each about 1 km long and 2 km wide). In each sector, the physical variables consisting of the geomorphology, geologic material and slope and tsunami hazard variables (tsunami wave height and inundation distance) and their ranking were calculated.

2.2.3 Results of the PVI computation

A summary of the ranking and Physical Vulnerability Index for each sector is represented in Fig. 8a, whereas Fig. 8b shows the PVI frequency distribution charts for the west coast of Langkawi Island. Based on these figures, the PVI distribution is summarized in Table 4 which will be described in Sect. 3 below.

2.3 Tier 3: micro-scale assessment (development of the Structural Vulnerability Index)

Results of the Tier 2 Assessment can then be used to identify the highly and very highly vulnerable areas prone to tsunami floods of the worst-case scenario. In the case of Langkawi (Fig. 8), sectors L6, L7, L8 and L9 were selected for the next level of assessment, that is, the determination of the physical or structural state of buildings in these areas. Before a micro-scale assessment could be conducted, an *exposure* database containing information about the physical and structural features present in the selected area including coastal structures, major infrastructures and important buildings was created, so that this information could be used to assess and predict the vulnerability of the area against a future tsunami of the worst-case scenario. The structural vulnerability assessment was based on a combination of results of the tsunami inundation modelling, information collected during the building inventory survey in February to March 2010 and the use of GIS to construct the vulnerability maps. The assessment was focused on the application of the revised *Papathoma Tsunami Vulnerability Assessment* (*PTVA-3*) M*o*del to assess building and structural vulnerabilities to the threat of a worst-case tsunami.

In this assignment, we were only interested in assessing the structural vulnerability of the buildings and did not focus on the assessment of the different building components due

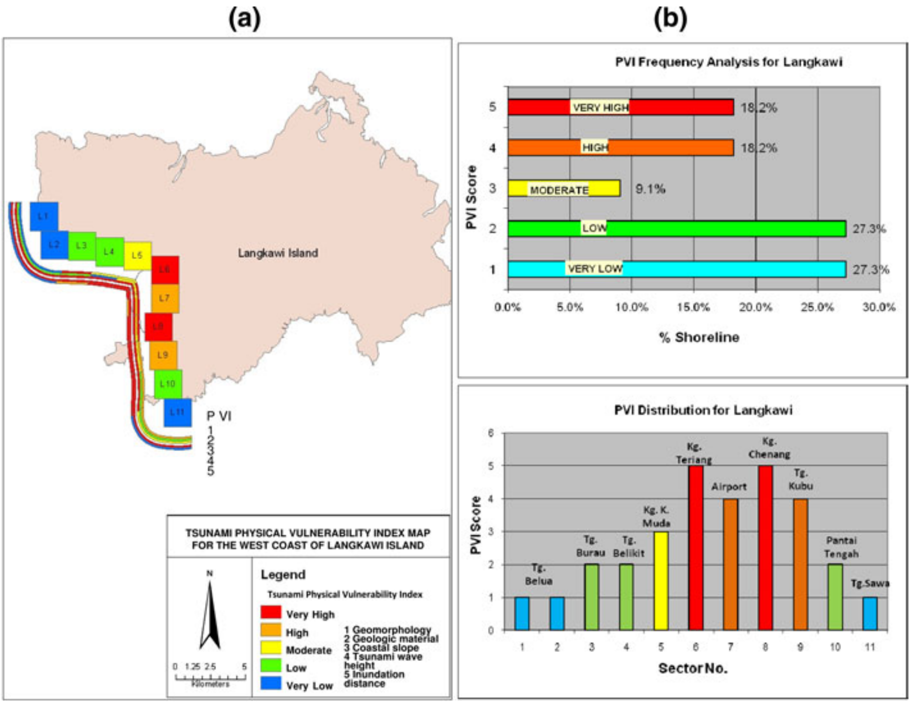


Fig. 8 **a**Tsunami Physical Vulnerability Index map and **b** PVI frequency analysis (*top*) and PVI distribution (*bottom*) for the west coast of Langkawi Island

Table 4 Distribution of the Physical Vulnerability Index along the west coast of Langkawi

PVI score	Total length affected (km)	Affected sectors	Potential affected villages
5	4.0	L6	Kg. Teriang, Kg. S. Kedak, Kg. K. Melaka
		L8	Kg. Chenang, Pantai Kuala Chenang
4	4.0	L7	Airport
		L9	Tg. Kubu, Kg. Lubok Buaya, Kg. Padang Puteh
3	2.0	L5	Kg. K. Muda
2	6.0	L3	Kg. Telok Burau, Tg. Burau
		L4	Tg. Belikit
		L10	Pantai Tengah
1	6.0	L1	Tg. Belua
		L2	Tg. Malai, Tg. Sawa
		L11	

to their prolonged contact with water. Hence, we have not used the WV parameter that was required in the computation of the Relative Vulnerability Index (RVI) as proposed in the original PTVA-3 model.

The structural vulnerability (SV) as a consequence of a tsunami hazard is characterized by features such as (i) the type of buildings or structures exposed to the tsunami flood, (ii) the presence of offshore barriers, (iii) distance from the shoreline and (iv) flood depth. After determining the flooded areas from the inundation model, the Structural

Vulnerability Index for each building in the inundation area was calculated based on the PTVA-3 model as given in Eq. (2):

$$\mathrm{SV} = \mathrm{Bv} * D_{\mathrm{prot}} * \mathrm{FD} \tag{2}$$

where

Bv building vulnerability that depends on the physical characteristics of the building that influence the resistance to a flood
D_{Prot} degree of protection provided for each building
FD flood depth at each building

The value for each of the parameters is assigned a ranking scale of −1 to 1, where −1 represents the lowest vulnerability and 1 represents the highest vulnerability. A brief description of the ranking system is provided in the following section.

2.3.1 Calculation of building vulnerability (Bv)

Dall'Osso et al. (2009a, b) outline the variables used to calculate the building vulnerability (Bv) as follows:

1. Number of stories
2. Building material
3. Ground-floor hydrodynamics
4. Foundation depth
5. Shape and orientation of building
6. Presence of movable objects
7. Overall condition of building

The variables were given the respective ranking as shown in Table 5. After measuring all the mentioned parameters for each building in the inundation area, the building vulnerability (Bv) was calculated using Eq. (3):

$$\mathrm{BV} = \mathrm{w}_1 a + \mathrm{w}_2 b + \mathrm{w}_3 c + \mathrm{w}_4 d + \mathrm{w}_5 e + \mathrm{w}_6 f + \mathrm{w}_7 g \tag{3}$$

where

w_i weight factor
a number of stories
b building material
c ground-floor hydrodynamics
d foundation type
e presence of movable objects
f shape and orientation
g overall condition of building

The same weight factors in building vulnerability (Bv), as originally proposed in the PTVA-3 model, were also used in our assessment of the SV parameter.

2.3.2 Calculation of degree of protection (D_{prot})

There are three parameters that need to be determined in order to calculate the degree of protection for the buildings in the inundation area. The parameters and their ranking are represented in Table 6. In this assessment, the PTVA-3 model as described by Dall'Osso

Table 5 Ranking of variables in calculating the building vulnerability (modified after Dall'Osso et al. 2009a, b)

Variable	Ranking				
	Very low 1	Low 2	Moderate 3	High 4	Very high 5
Number of stories	More than 5 stories	4 stories	3 stories	2 stories	1 storey
Building material	Reinforced concrete		Semi-permanent	Single Brick	Wood
Ground floor hydrodynamics	Open plan	Open plan and windows	50 % open plan	Not open plan, many windows	Not open plan
Foundation type	Deep foundation		Average foundation		Shallow Foundation
Movable objects	No	Moderate	Average	High	Extreme
Shape and orientation	Rounded or triangular building footprint	Square building footprint with oblique orientation OR lengthened rectangular footprint with the main side perpendicular to the shoreline	Rectangular building footprint with the main side perpendicular to the shoreline, OR slightly oblique	Square building footprint OR rectangular with the main side parallel to the shoreline	Lengthened rectangular building footprint with the main side parallel to the shoreline
Preservation condition	Excellent	Good	Average	Poor	Very poor

et al. (2009a, b) has been adjusted to match our study area. For example in Malaysia, most of the houses are not surrounded by a brick wall, so we have omitted this parameter from the model. We have also decided to use a maximum water depth of 3.0 m instead of 5.0 m used in the PTVA-3 model. The reason is that reported tsunami heights for the affected areas in Malaysia were found to be less than 3 m high. After gathering all the required inputs described earlier, the degree of protection was calculated using Eq. (4):

$$D_{\text{prot}} = \mathrm{w}_1 a + \mathrm{w}_2 b + \mathrm{w}_3 c \tag{4}$$

where

w_i weight factor
a building row no.
b presence of natural barrier
c presence of coastal barrier

Here, the PTVA-3 model has been modified in order to represent the local building scene in which the effect of brick walls around the houses had been omitted and the weight factors were adjusted so that the sum of the weight factor remains one.

The adjusted formula is:

Table 6 Ranking of variables in calculation of the degree of protection (modified after Dall'Osso et al. 2009a, b)

Variable	Ranking				
	Very low 1	Low 2	Moderate 3	High 4	Very high 5
Building row	$\geq$ 10th	7th–9th	4th–6th	2nd and 3rd	1st
Natural barrier	Very high protection	High protection	Moderate protection	Low protection	No protection
Coastal barrier	Vertical structure with height more than > 3.0 m	Vertical structure with height between 2.0 and 3.0 m	Vertical structure with height between 1.0 and 2.0 m	Vertical structure with height between 0.0 and 1.0 m	Slope structure with height between 0.0 and 1.0

$$D_{\mathrm{prot}} = 1/246\,(100 * \text{ Building row} + 73 * \text{ Natural barrier } + 73 * \text{ Coastal barrier}) \tag{5}$$

The same weight factors for both natural and man-made barriers were used because the effectiveness of them in reducing the tsunami risk has not been fully validated yet.

2.3.3 *Calculation of flood depth*

It is evident that one of the most significant parameters that could contribute a significant level of tsunami damage to buildings is flood depth (Reese et al. 2007; Omira et al. 2009). Flood depth is also ranked from 1 (very low) to 5 (very high) as shown in Table 7. However, the values have been adjusted, so that the maximum flood depth remained at 3 m as opposed to 5 m used in the PTVA-3 model.

2.3.4 *Building survey*

A building survey was conducted to gather the information required to calculate the structural vulnerability for each building in the inundated areas. A spreadsheet containing the building details was prepared and used during the field survey. Most of the buildings are of typical Malay "kampong" or village houses belonging to fishermen and private owners, whilst commercial buildings are mainly tourist resorts and shops. These buildings are mainly made of timber and are either raised on wooden stilts or semi-permanent in nature. The latter is normally half-wood and half-concrete, and it can be one- or two-storey building. Examples of buildings typically found in Langkawi and also in most parts of the country are illustrated in Fig. 9. The gathered data together with some additional data from airborne LIDAR orthoimages were used to calculate the Structural Vulnerability Index.

Table 7 Ranking of Flood Depth in SVI

Variable	Ranking				
	Very low 1	Low 2	Moderate 3	High 4	Very high 5
Flood depth (m)	<0.5	$0.5 \leq x < 1$	$1 \leq x < 2$	$2 \leq x < 3$	≥ 3

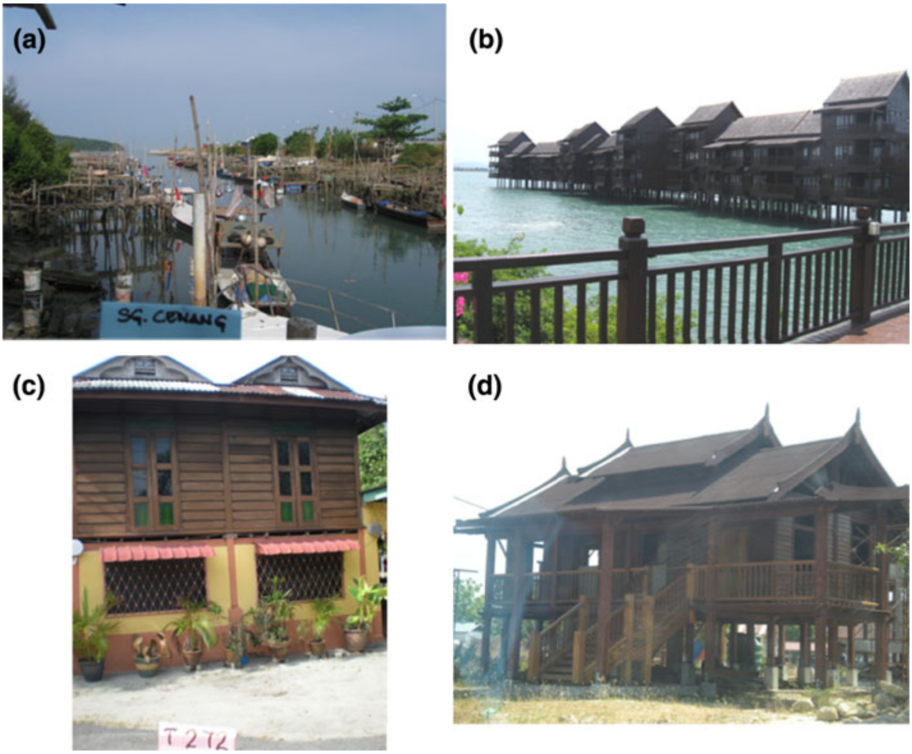


Fig. 9 Samples of buildings in the Study Area **a** fishing vessels and wooden huts at the river mouth of Kg. Chenang; **b** a row of wooden chalets in a seaside resort at P. Chenang; **c** a typical "semi-permanent" 2-storey house with a timber top floor and concrete lower floor; **d** a raised wooden house with open concept

The results were superimposed to the building shapefile in the GIS to show the structural vulnerability based on the colour code ranking for each building.

2.3.5 Results of the SVI computation

The Tsunami Physical Vulnerability Index map obtained from the local-scale assessment showed that sector L6 and sector L8 are two areas that are ranked as very highly vulnerable. These areas are known as Kg. Teriang and Chenang, respectively, and were reported to have suffered severely during the 2004 tsunami.

Kg. Teriang is a crowded village located to the north-west of Langkawi airport with many local fishermen living in the area. This area was highly affected by the 2004 tsunami and suffered a lot of damages. Chenang area, on the other hand, is a very crowded tourist area with many hotels, resorts and shops located there.

The exposure database for the Teriang and Chenang areas has been divided into five and eleven subsections, respectively. A total number of 1,024 buildings are expected to be inundated by the tsunami flood. Table 8 shows the distribution of building types exposed to the hazard. Results of the SVI computation are presented in the form of a SVI Map to differentiate the structural vulnerability of each exposed building in the area based on the colour code ranking. Blue colour is used for lowest vulnerability, and red is for the highest

Table 8 Distribution of building types in the west coast of Langkawi Island

Building type	Description	No. of buildings	% Occurrence
Type 1	Private residential building	524	51.17 %
Type 2	Public building (hospital, school, etc.)	44	4.30 %
Type 3	Commercial building	106	10.35 %
Type 4	Government building	8	0.78 %
Type 5	Tourism building	342	33.40 %
Type 6	Others	0	0.00 %
	Total number of buildings	1,024	

vulnerability. The Structural Vulnerability Index has been calculated for all the buildings in these subsections as shown in Fig. 10 for Teriang and Chenang areas. Details of the results in the form of individual maps for all the buildings in the affected sectors are provided in Ismail et al. (2010).

Based on a frequency analysis of all exposed buildings in the affected area, the distribution of the structural vulnerability of the built environment in Langkawi Island is summarized in Table 9.

3 Discussion of results

The first part of the assessment (macro-scale) as described previously shows that Langkawi Island is one of the areas that will be highly impacted from future tsunamis. Therefore, a physical vulnerability assessment has been conducted for this area. In general, it is

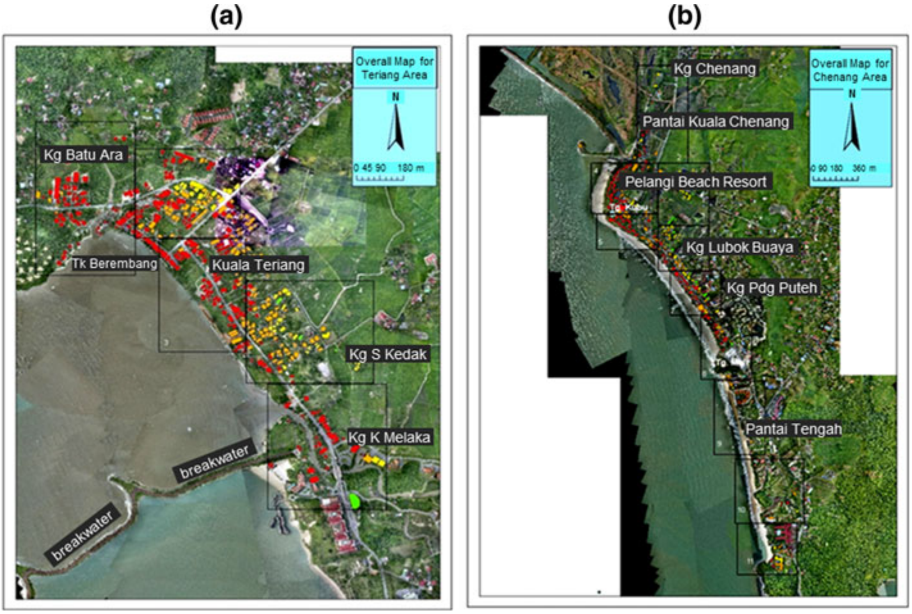


Fig. 10 Structural Vulnerability Index map for **a** Teriang and **b** Chenang areas, Langkawi

Table 9 SVI frequency analysis for buildings along the west coast of Langkawi

Frequency analysis for structural vulnerability			Location
Rank	No. of buildings	% Occurrence	
Very high	546	53.32 %	Kg. Batu Ara, Kuala Teriang, Kg. S. Kedak, Kg. K. Melaka, Kg. Padang Puteh, Pelangi Beach Resort
High	298	29.10 %	Kuala Teriang, Kg. S. Kedak, Kg. Padang Puteh
Moderate	144	14.06 %	Kg. Lubok Buaya, Kg. Padang Puteh, Kg. S. Kedak
Low	36	3.52 %	Kg. Lubok Buaya, Kg. Padang Puteh, Tg. Mali
Very low	0	0.00 %	–

observed that 18.2 % of the shoreline along the west coast of Langkawi Island is classified as very highly vulnerable to tsunami impact of the worst-case scenario. These areas are identified as sectors L6 and L8. The geomorphology of these two areas is mainly depositional features and narrow sandy beaches, and the river mouth of Sungai Melaka is located in sector L6. The geologic materials are composed of sand, silt and clay, whilst the coastal slope is very gentle. The tsunami wave height is ranked as very high (>3 m), and inundation distance is expected to be 1,600 m for sector L6 and 1,900 m for sector L8. Sectors L1, L2 and L11 are ranked as having very low vulnerability to the worst-case tsunami impact. These account for 27.3 % of the shoreline. Sectors L1 and L2 are rocky cliff, and sector L11 has a wide beach to the north and rocky cliff to the south. All three sectors are ranked low in terms of geologic material. In sectors L1 and L2, these materials are fine- to medium-grained sandstone with subordinate coarse-grained, whilst sector L11 consists of sandy beach and rock of black shale. Like most of the other sectors, the coastal slope in sectors L1 and L2 is gentle, but in sector L11, the slope is steeper and ranked as moderate. Although the tsunami wave height is ranked very high for all of these three sectors, tsunami inundation distance was negligible. Hence, the tsunami inundation distance was ranked as very low. The combination of these parameters results in very low vulnerability for the shoreline in sectors L1, L2 and L11.

Since sectors L6 and L8 (Kg. Teriang and Chenang areas) have been identified as very vulnerable in terms of physical characteristics of the coastline, a micro-scale assessment has been conducted for these two areas.

A total of 1,024 buildings are situated within the inundated zone area during the worst-case tsunami event; 51.17 % of the potentially inundated buildings are of the residential type, 33.40 % are tourism type, 10.35 % are commercial buildings, and the rest (government, public buildings) make up almost 5 %. A total of about 82.42 % of the buildings along the west coast of Langkawi are classified as highly to very highly vulnerable to the tsunami floods. Out of this, almost 53.32 % of the buildings are very highly vulnerable. In addition, 14.06 % of buildings are ranked as moderately vulnerable, and only 3.5 % of buildings are in the low vulnerability category.

Among the very highly vulnerable buildings in the study area, 499 buildings were made of wood or single brick and 65 were constructed of a combination of wood and brick. Many of the wooden houses belong to the local fishermen, and they tend to build their houses near the sea or at the river mouths. Several wooden buildings identified in Chenang area were chalets belonging to hotels and resorts. Although they are in a much better condition compared to the fishermen's wooden houses, they may not be able to stand against the tsunami impact too.

4 Appraisal of results and recommendations

One specific outcome of the study was the production of Tsunami Impact Classification Maps that are needed to evaluate and classify the different parts along the north-west coast of Peninsular Malaysia that are vulnerable to tsunami impacts by a tsunami generated from the Sumatra–Andaman fault. These maps are important for disaster planners and coastal managers for planning and preparing effective countermeasures such as planning for future developments or providing protection for areas that are most prone to the future events of a tsunami. Subsequently, the construction of the PVI maps will then serve several purposes for potential use in a Coastal Zone Management Decision Support System by providing a classification system and database as guidance to authorities in drawing out their development plans, structure plans, coastal defence plans and optimum layout of agriculture areas.

The micro-scale assessment that identified the structural vulnerability of a specific locality is important in determining the level of risks of the tsunami impacts on the built environment. This study focuses on the application of the PTVA-3 model which has been adjusted to assess building and structural vulnerabilities to the threat of a worst-case tsunami in the coastal area of Langkawi. These areas are characterized by an impressive economic importance due to the presence of major infrastructures such as an international airport and also tourist destination sites which attract an influx of tourists during high season. Hence, in case of a tsunami attack, the economic and human loss in these areas could be considerable. Also, the flat topography may increase the risk of inundation and hence incur high risks to the safety of buildings and properties in these areas.

Hence, results of the assessment, in the form of various levels of GIS-based maps such as the Tsunami Impact Classification Map, PVI and SVI maps, may be applied by several different end-users, respectively, as follows:

1. As a basis for planning tsunami mitigation measures by disaster planners/coastal managers at the federal level;
2. Assisting state and municipal/local planning authorities in making decisions related to permitting development in different tsunami flood zones at the state and district levels;
3. As a tool for relief agencies in the planning of evacuation routes and shelter areas at the local level.

Based on the results of the assessment, mitigating measures were proposed for the highly and very highly vulnerable sectors in Langkawi, as summarized in Table 10. Some recommendations of evacuation routes and tsunami shelters for sectors L6 and L8 in Langkawi are shown in Fig. 11. It is also recommended that these maps be further publicized to the local communities.

5 Conclusions

The aftermaths of the December 2004 tsunami caused a grave concern to the Government of Malaysia over the life-threatening situation of its coastal areas. Therefore, in order to provide a better countermeasure to future tsunami events, a comprehensive tsunami vulnerability assessment study has been conducted for the north-west coast of Peninsular Malaysia. A three-stage methodology has been applied, namely a macro-scale, local-scale and micro-scale assessment. A scenario-based tsunami modelling has been applied in the macro-scale assessment. It is concluded that the worst tsunami event that may affect the

Table 10 Proposed mitigation measures for very highly vulnerable sectors in Langkawi

Sector No.	Location/area	PVI score	Structural vulnerability index (SVI)			Proposed mitigation measures
			Ranking	(%)	No. of buildings	
L6	Kg. Sungai Kedak, Kuala Sungai Melaka, to Kampung Kuala Muda	5	Very high	59.32 %	105	Accommodate • Provide evacuation routes and identify tsunami shelters Protect • Rehabilitate mangroves to the north Maintain and deepen Sg. Melaka and other drainage systems • Raise heights of retaining walls around reclaimed areas
			High	29.94 %	53	
			Moderate	8.47 %	15	
			Low	2.26 %	4	
			Very Low	0.00 %	0	
L8	Pantai Chenang, between airport in the north and Kg. Chenang to the south	5	Very high	56.00 %	14	Accommodate • Identify a safe tsunami shelter Protect • Raise the heights of retaining walls around reclaimed areas • Improve all drainage systems
			High	28.00 %	7	
			Moderate	16.00 %	4	
			Low	0.00 %	0	
			Very low	0.00 %	0	

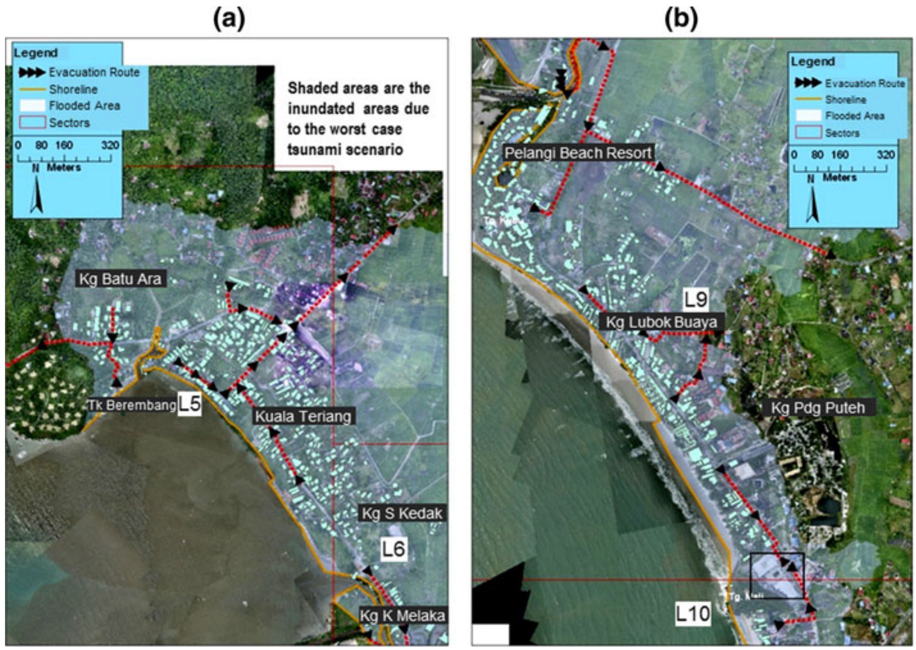


Fig. 11 Proposed evacuation route for **a** Sector L5-L6 and **b** L8-L10 in Langkawi

north-west coast of Malaysia has a same source as the 2004 Indian Ocean Tsunami that could happen during the highest astronomical tide level. As a result, some parts of the north-west coast of Malaysia including Langkawi Island were ranked as very highly vulnerable to the worst-case tsunami. The vulnerability of the Langkawi coastline itself has been assessed at a local stage, and the results of the assessment have been presented in the form of a Physical Vulnerability Index map. It was shown that 36.4 % of the west coast of Langkawi was ranked as highly and very highly vulnerable, whereas 63.6 % was ranked as moderate to very low vulnerability. A structural vulnerability (micro-scale) assessment was then conducted for the Teriang and Chenang areas that had been ranked as very highly vulnerable to tsunami impact in the local-scale assessment. The results of the micro-scale assessment showed that many of the buildings that are very highly vulnerable to tsunami impact are made of wood and single brick layers. These buildings are mainly located near the shoreline, and they are expected to suffer more damage. The results of this assessment were used to produce a Structural Vulnerability Index (SVI) map which facilitates in identifying the various levels of impact severity towards existing building structures, property and land use and will also indicate the vulnerability of the resources and human settlements within the study area. Consequently, results of the assessment could help planners to establish a zoning scheme for potential coastline development based on the area's sensitivity to tsunami of the worst-case scenario. Some recommendations of evacuation routes and tsunami shelters in the potentially affected areas were also proposed to the Government as a tool for relief agencies to plan for safe evacuation. Thus, Malaysia has accepted the fact that it is no longer in the "comfort" zone by presenting itself a carefully planned mitigation scheme in preparedness of a future tsunami attack.

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