2004 Indian Ocean Tsunami in Malaysia

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The tsunami is one of the deadliest natural disasters, responsible for more than 260,000 deaths and billions in economic losses over the last two decades. The footage of the devastating power of the 2004 Indian Ocean tsunami perhaps remains vivid in the memory of most survivors, and Malaysia was one of the countries affected by the unprecedented 2004 tsunami. It was the first time the Malaysian government had managed such a great disaster. A compilation of post-event observations regarding tsunami characteristics is first presented in the form of maps, followed by building damage, including damage modes of wall failure, total collapse, debris impact and tilting of structures.

2004 Indian Ocean tsunami Malaysia disaster risk

1. Introduction

Since ancient times, tsunamis have been observed and reported, especially in Japan, Indonesia, and the Mediterranean areas. Historically from 1901 to 2016, the Pacific Ocean was the main tsunamigenic region: approximately 75% of tsunami events occurred within its basin, compared to 10% in the Atlantic, 9% in the Mediterranean region, and 6% in the Indian Ocean [1]. Tsunamis are catastrophic in nature; the huge volume of sea water mobilized with very high energy is capable of overtopping shorelines and coastal zones rapidly. A devastating tsunami can cause a series of widespread impacts such as destruction of seaside villages, significant damage to cars, buildings and infrastructures, post-tsunami disease outbreaks and fatal consequences [2].

In 2004, Malaysians had not expected that a tsunami could sweep into the northwest shore of Peninsular Malaysia (West Malaysia) through the north entrance of the Straits of Malacca. The unprecedented 2004 event claimed 74 lives (with 68 reported dead and 6 missing) and caused 300 injuries [11,12], thus changing the mindset of citizens that the country was safe against tsunamis. According to a survey conducted by Lau et al. [13], about 84% of the respondents agreed that the degree of preparedness of Malaysians to take appropriate actions during the occurrence of natural hazards was still insufficient. The aftermath of the disaster has caught the attention of the Malaysian government, spurring it to formulate an effective solution for building a resilient society [14]. Subsequent measures include the assessment of tsunami threats, mitigation of tsunami risk, enhancement of tsunami preparedness, development of tsunami emergency response plans (TERPs), rehabilitation and reconstruction. Nevertheless, Malaysia's design of coastal structures in accordance with relevant standards and codes is still halted at the infant stage due to a lack of knowledge on tsunami impact topics.

2. 2004 Indian Ocean Tsunami: Field Observations in Peninsular Malaysia

On 26 December 2004, the first-ever tsunami in Peninsular Malaysia was recorded in the modern history of Malaysia. Notwithstanding its proximity to the earthquake's epicentre (west coast of northern Sumatra), Malaysia escaped the severe damages and casualties suffered by the neighbouring countries, including Sri Lanka, Thailand and Indonesia (particularly Banda Aceh). Although the 2004 tsunami event only affected those states in the northern half of the Straits of Malacca, this incident was considered one of the most critical disasters among the 39 disasters experienced in Malaysia from 1968 to 2004 [15] and the 51 natural disaster events from 1998 to 2018 [16]. It brought both short- and long-term sequelae to the locals, including physical, environmental, socio-economical and even psychosocial impacts [17,18]. This thus gathers field-investigated data in the following sub-sections, focusing on the tsunami's characteristics and the building damage in the inundation zones at different tsunami-affected locations. The summarized information could provide additional knowledge to coastal communities on tsunami-related topics.

2.1. Tsunami Characteristics

In Malaysia, the major tsunami-affected areas were the northern coastal areas, particularly Kuala Muda and the outlying islands (Penang Island and Langkawi Island). Five locations each on Penang Island (Batu Ferringhi, Tanjung Tokong, Tanjung Bungah, Pantai Acheh and Gurney Drive) and Langkawi Island (Pantai Tengah, Pantai Cenang, Kuala Teriang, Pantai Kok and Sungai Melaka), and six major locations in Kuala Muda (Kota Kuala Muda, Tanjung Dawai, Kuala Sungai Muda, Kampung Tepi Sungai, Kg Masjid and Padang Salim) were badly hit by the 2004 Indian Ocean tsunami. It is reported by Yalciner et al. [19] and Bird et al. [20] that the waves first reached Langkawi Island slightly more than 3 h after the earthquake, with an average speed of 240 km/h and nearshore positive amplitudes ranging from 2.5 m to 3.0 m. The waves subsequently travelled south to Penang Island with average nearshore positive amplitudes ranging between 2.0 m to 3.0 m, while a lower speed of approximately 100 km/h occurred across the Straits of Malacca due to the shallower sea depth [21].

Field-investigated data are critical to the fundamental understanding of tsunami generation and propagation as well as the coastal impacts. Subsequent to the 2004 Indian Ocean tsunami, post-disaster surveys and case studies were extensively conducted at Penang Island, Langkawi Island and Kuala Muda [19,20,21,22,23,24]. The variability of tsunami flow characteristics is based on a site-specific basis in terms of geomorphic setting. Thus, the tsunami wave parameters from observations such as the maximum runup height, which could be helpful as a benchmark for the validation of tsunami inundation models.

The findings compiled show that the maximum runup reached as high as 6–8 m (Pasir Panjang), 4 m (Teluk Ewa) and 3.8 m (Kota Kuala Muda) at Penang Island, Langkawi Island and Kuala Muda, respectively. As reported, the maximum tsunami inundation ranged from 13 m to 3000 m, depending on the ocean bathymetry, topography, hydrology and geology of the coast [11]. The variability is also attributed to tsunami barriers or other coastal protection structures. In Malaysia, the man-made offshore breakwaters and seawalls along the coastline in the south of Kuala Teriang did help to reduce the tsunami wave inundations [19,22,27]. However, Lee et al. [28] reported that certain landward areas in Kampung Kuala Teriang still failed to be protected by those man-made structures. On the other hand, the wave energy was successfully dissipated by natural barriers such as the mangrove forests found at Pantai Acheh, resulting in a runup height of less than 4 m [23]. The northern parts of Langkawi Island (Kampung Kubang Badak) and Kuala Muda (Kampung Pulau Sayak) also suffered less impact, as they were shielded by mangrove forests [28,29].

As for the flow velocity, there is limited relevant information recorded for the 2004 tsunami event in Peninsular Malaysia. Komoo and Othman [24] reported that the flow velocity for the wave approaching Kuala Muda was approximately 8.33 m/s, whereas a flow velocity of approximately 18.06 m/s was observed for Penang Island and Langkawi Island. This observation is somewhat contrary to the study of Bird et al. [20], which reported a much lower flow velocity of 6.94 m/s near Sungai Kuala Triang in Langkawi Island.

2.2. Building Damage

According to the Department of Irrigation and Drainage (DID), a total of 1535 residential buildings in Malaysia—in Kedah (900), Penang Island (615) and Perak (20)—were damaged or destroyed during the 2004 tsunami event [22]. The affected buildings were classified into wooden/timber houses, masonry houses and combination wooden and masonry houses. Kedah (particularly the Kuala Muda region) was deemed one of the most severely affected areas among the affected states of Malaysia. Apart from its low-lying coastline, most of the houses in Kuala Muda were made of highly vulnerable wooden frames made up of columns and beams which were supported closely by spaced joists.

Regarding the aspect of structural damage, buildings with different structural systems and construction materials suffered different extents of destruction. Based on the surveyed data, as in DID [22], Komoo and Othman [24] and Nordin and Charleson [30], such damage modes as wall failure, total collapse, debris impact and tilting of structures were commonly observed along the northwest coast of Malaysia. Accordingly, both wooden and masonry houses suffered wall failure when impacted by tsunami waves. The wall panels of those wooden houses suffered enormous damage as the strong surges completely washed them away and consequently lifted and swept away floors and roofs as well. On the other hand, though most of the masonry houses managed to stand intact, their frontal faces suffered severe damage, owing to the direct exposure of their large surface areas to tsunami waves. Some portions of roof tiles were also found to be damaged by wave-induced uplift forces. The worst possible scenario is the wall blowout. This phenomenon shows that hydrodynamic forces act on both the exterior and interior wall panels during the tsunami flows through a building.

Collapse is the most common failure observed for wooden houses. Often, little is left of the wooden constructions after they are subjected to the wave-induced loads [31]. Those constructions are vulnerable to the waves' hydrostatic and hydrodynamic forces, though they resist earthquake loadings with minor damage. As a sequela of extreme hydrodynamic events like tsunamis, wooden houses were easily disintegrated into the sub-structures and were washed away as waterborne debris. Furthermore, some masonry houses located along the beaches of

Kampung Masjid and Kampung Tepi Sungai in Kedah were also found to have collapsed, which could be attributed to lower structural strength, as the masonry houses are non-engineered lightly reinforced concrete (RC) buildings. Collapse generally occurs once the wave-induced loads exceed the load-carrying capacity of a building, especially when there is no coastal protection along the coastline.

Tsunami loads might become more destructive with mud-laden waves and debris resulting from vehicles and failed building components such as wall panels, windows and roofs. With each passing cycle of inflow and outflow, the amount of debris could increase as the waves sweep everything present in the inundation zones [32]. This kind of destruction was apparently reported on Langkawi Island and Penang Island [20,21]. During the 2004 tsunami occurrence in Peninsular Malaysia, the debris of floating vehicles was carried by the tsunami flow and was deposited at houses. When a wave carrying large-scale debris surged toward the houses, the houses were laden with debris and subsequently experienced severe damage to exterior walls and structural columns, as well as beams.

Another failure mode was observed in Kota Kuala Muda: tilting of structures. This scenario mainly involves traditionally designed Malay houses with a combination of wooden and masonry structures. Such traditional houses survived in the 2004 tsunami event, as their elevated design provided enough space for low tsunami waves to go underneath, and thus the first floor was hardly affected [30]. For this kind of structure, the piers and house-to-stump connections play essential roles in resisting the waves and debris impact. Due to the failure of columns on the ground floor, the whole structure was tilted, associated with large deformation. However, the damage experienced by an elevated house is said to be significantly related to the tsunami inundation depth. The whole structure could be destroyed in the worst scenario where the inundation depth is high enough to reach the first floor.

The Malaysian government commenced post-disaster rehabilitation and reconstruction in the immediate aftermath of the disaster. Other than the financial aid, temporary housing of timber and steel longhouses was constructed to provide safe shelter for about 104 affected families whose houses were no longer inhabitable [33,34]. A new town development plan with permanent housing was then undertaken by the national housing development company (SPNB), owned by the minister of finance of Malaysia, to relocate the tsunami victims. Under the “Rumah Mesra Rakyat” (RMR) Program, 561 new permanent houses were built in Penang State (Pangsapuri Masjid Terapung in Tanjung Bungah, Desa Kuala Muda in Seberang Perai), and 166 others were built in Kedah State (Taman Ara Jaya in Langkawi, Taman Permatang Katong in Kota Kuala Muda) [35]. This emergency housing has been met with great satisfaction among the affected communities in Kota Kuala Muda.

3. Assessment of Tsunami Threats to the Coast of Malaysia

3.1. Tsunami Hazard Zoning

In the foreseeable future, tsunamis will likely threaten Malaysian coastal dwellings [36]. Based on the tectonics of the Southeast Asia region, the Malaysia region is situated on the Sunda Plate, bordered by seismically active areas. In the assessment of tsunami threats to Malaysia, significant uncertainties exist regarding the potential tsunamigenic earthquake sources originating from the Andaman Nicobar Islands fault slip zone, Philippine subduction zones, the South China Sea (SCS), the Sulawesi Sea and the Makassar Strait [36].

In 2009, the Ministry of Science, Technology and Innovation (MOSTI) initiated the development of a tsunami hazard map for Malaysia based on the above-mentioned potential sources. According to the tsunami hazard zones depicted, not all parts of Malaysia will have the same degree of tsunami risk. The risk areas can be sub-divided into two zones of different degrees of risk: Zone 1 can be defined as the high vulnerable hazard zone, covering the northwestern part of Peninsular Malaysia (Perlis, Penang, Kedah, Perak and Selangor) as well as the northeast, northwest and southwest coasts of Sabah (Kudat, Kota Kinabalu, Sandakan, Lahat Datu, Semporna, Tawau and Sipadan), whereas Zone 2 possesses no or very low tsunami hazard, covering the remaining coastal areas in Malaysia. Note that Sabah is a Malaysian state located in East Malaysia.

3.2. Worst-Case Scenario Simulation

Although the established tsunami warning systems could save lives through the early evacuation of residents, understanding inundation scenarios is crucial to resilience preparation. Following the 2004 tsunami event, great efforts by means of computational simulations have been seen, focusing on the three main phases of tsunami dynamics: generation, propagation and runup. According to the literature, tsunami simulations are commonly performed using the following well-known models: the COMCOT (Cornell Multi-grid Coupled Tsunami model), TUNAMI, TUNAMI-N2, TUNAMI-N2-NUS (Tohoku University's Numerical Analysis Model for Investigation of the Near-field tsunami), TDP (Tsunami Display Program model), TUNA, TUNA-M2, TUNA-RP (Tsunami-tracking Utilities and Application) and MIKE 21 flow model, developed by the Danish Hydraulic Institute (DHI).

Prior to the investigation of potential worst-case events, the scenario of the 2004 tsunami generation and propagation towards Malaysia was first reconstructed, and the simulation results were compared with the post-tsunami observations [23,37,38,39,40,41,42]. The study of Ghazali et al. [43] suggested the possibility of a 2004 tsunami scenario coinciding with the highest astronomical tide (HAT) event that would double the tsunami incident waves and inshore penetration observed in 2004. Apart from the simulation based on the tsunami back in 2004, other extensive tsunami modelling efforts with multiple scenarios and possible sources have also been undertaken to identify the locations at risk. The findings from the worst-case scenarios of future tsunamis striking the Malaysian shores (Peninsular Malaysia (particularly Perlis, Kedah and Penang Island) and East Malaysia (particularly Sabah)) were compiled, respectively. The forecasted key parameters include the tsunami arrival times, wave heights, inundation depths, runup heights and flow velocities to which coastal communities would be subjected.

Based on historical earthquake data along the Indian/Burma Plate, Ismail and Wahab [44] and Karim et al. [45] assessed the tsunami threat along the northwest coast of Peninsular Malaysia. Considering an earthquake magnitude (Mw) of 9.0, Kuala Triang received the highest tsunami level of around 5 m above the MSL. As evident from the worst-case scenario simulation, the other possible affected areas in Peninsular Malaysia include Teluk Bahang, Pasir Panjang and Georgetown in Penang Island, Kuala Triang and Teluk Ewa in Langkawi Island, Kuala

Muda and Kuala Sanglang. Apart from the threat imposed from the Indian Ocean (Indian/Burma Plate), Koh et al. [23] demonstrated the severe impacts caused by tsunamigenic earthquakes at the Sumatra–Andaman fault, which might result in runups as high as 7.5 m at Langkawi Island and Penang Island. The recent study of Naim et al. [46] attempted to revise inundation results due to coastal changes and the availability of better topographic data. The latest findings show that Penang Island would be susceptible to being inundated 3.47 km inland to a depth of 5.40 m, triggered by earthquakes of Mw 9.25 along the Sunda Trench. There are also potential tsunami sources in the SCS due to the fault rupture along the Manila Trench near the Philippines affecting the east coast of Peninsular Malaysia, especially the states of Kelantan and Terengganu [47].

As for East Malaysia, the earliest study of Raj [48] reported that the coastal areas of Sabah generally possess an insignificant tsunami threat. However, subsequent studies have demonstrated the tsunami risk originating from the Manila Trench [49,50,51,52,53,54], Sulu Trench in the Sulu Sea [55,56,57], North Sulawesi Trench in the Celebes Sea [58] and Cotabato Trench [59,60]. Based on the worst-case scenario findings, the affected areas include Tambisan Island, Sandakan, Berhala Island, Kudat, Lahat Datu, Tawau, Kota Kinabalu, Kota Belud, Labuan, Balambangan Island, Banggi Island and Semporna. Based on the study of Nurashid et al. [56], the first wave hit Tambisan Island about 22 min after the earthquake occurrence at Sulu Trench, in which the maximum inundation depth reached 8 m following an 8.8 magnitude earthquake. Pedersen et al. [58] also identified the potentiality of the Negro Trench generating tsunamis with a maximum wave of 3 m (along the coastline) that would strike the northern tip of Sabah.

In 2007, a giant potential landslide tsunami source was identified near the North-West Borneo Trough, the so-called “Brunei slide". To investigate its potential tsunami hazards towards Malaysia, Chai [61] and Tan et al. [62] computed a Brunei landslide tsunami simulation using the non-deforming submarine landslide model suggested by Watts et al. [63]. According to their studies, the Brunei slide-induced tsunami inundation distance might reach up to 2.64 km in Kota Kinabalu if the sliding slope is a 4° slope. In addition to the western region of Sabah, the coastal land of Sarawak (a Malaysian state located in the southwestern part of East Malaysia) could also be badly affected, with the inundation depth and distance potentially reaching 15.5 m and 4.86 km, respectively, for the worst scenario of a Brunei slide with a 4° sliding slope [62]. The later study of Ren et al. [64] also proved that not only Malaysia but also the coasts of Brunei, Indonesia, Vietnam, the Philippines and South China could be struck by Brunei slide-induced tsunamis as well. These findings are contrary to the hazard zones identified by the MOSTI [36], which state that the coast of Sarawak possesses a low tsunami hazard. The MOSTI needs to continue improving and updating the current tsunami hazard map by including the Brunei slide as a potential tsunami source, as landslide tsunamis have been receiving more attention in recent years.