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A STUDY OF THE EDGE WAVE EFFECTS INDUCED BY THE TSUNAMI OF 26 DECEMBER 2004 AT PHI-PHI ISLAND IN THAILAND

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ABSTRACT

The present study compares experimental laboratory results of the edge wave effect along Phi-Phi Island in Thailand with field-trip observations taken after the 26 December 2004 tsunami. A physical model of the island was constructed, with vertical scale of 1:500 and horizontal scale of 1:2500 in a 6×6 m steel tank. Waves were generated by the sudden opening of a gate releasing water from an elongated rectangular reservoir (6m×0.5m×0.6m). The initial tank water level was adjusted to simulate tsunami waves of various heights. The experimental observations focused on input wave heights, speed of propagation and the effect of edge waves on tsunami run up heights. The results explain how edge wave propagation was strongly affected by the size and shape of Phi-Phi Island and how it contributed to greater destruction. Additionally, the experimental observations provide valuable benchmark results that can help calibrate and validate numerical tsunami models.

KEYWORDS: Edge wave, Phi-Phi Island, tsunami, run up height, tombolo,

INTRODUCTION

The tsunami generated by the December 26, 2004 earthquake (Mw= 9.3) near the coast of Sumatra (Fig.1a) killed over two hundred twenty thousand people. The earthquake resulted from crustal movements along a region where the Indian/Australian tectonic plate subducts the Burma subplate of Eurasia (Fig. 1b). Research was undertaken because of concern that Hong Kong and other coastal regions of the South China Sea may be also vulnerable to future tsunami impact from earthquakes where the Eurasian and Philippine tectonic plates collide – a region known for frequent seismic and volcanic activity. As part of this research in evaluating potential tsunami risks, a 4-day field survey was made to Phuket and Phi-Phi Island in Thailand, from Feb 4-7, 2005, for the purpose of examining tsunami damage along the coastline of the island (Fig.2). The present study focuses on experimental modeling of tsunami effects at Phi-Phi Island and compares the results with what was observed in the field, for the purpose of obtaining a better understanding of how edge waves associated with a tsunami, could potentially affect and impact Hong Kong. The present paper is divided into three sections. The first describes briefly field observations of edge wave induced by the tsunami at Phi-Phi Island. The next summarizes previous studies of physical hydraulic modeling of edge waves. Lastly, the third section provides details of the physical modeling on how edge wave affected the coastline of Phi-Phi Island.

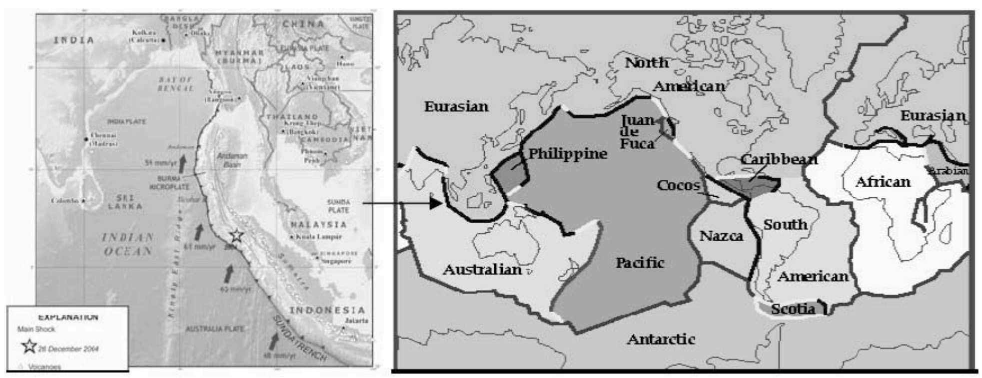


Figure 1 (a) Source Region of the 2004 earthquake; (b) Major tectonic plates.

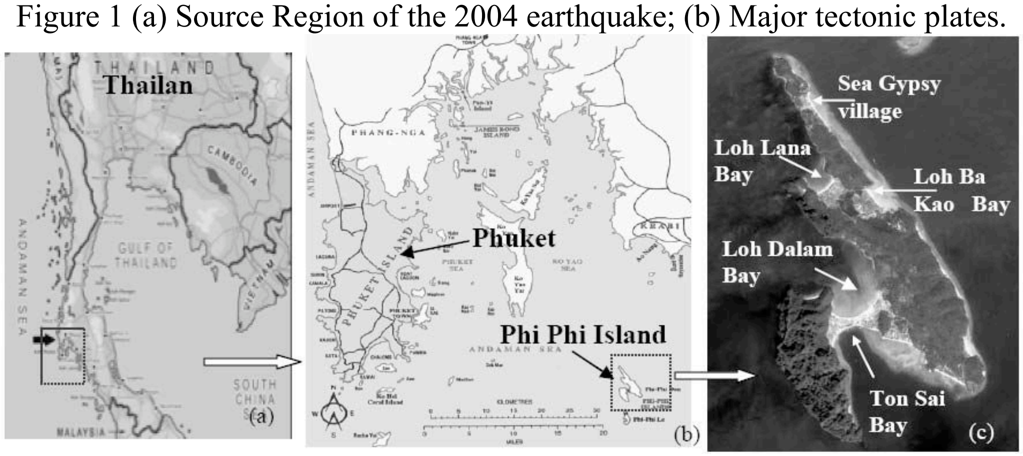


Fig. 2 Location of Phuket and Phi Phi Island in Thailand.

2. FIELD RECONNAISSANCE - PHI PHI ISLAND

Phi-Phi Island consists of two small narrow islands connected with a tombolo as shown in Figure 2c. The orientation of the two islands is roughly in a NNW direction. The length of the easternmost section of the island is about 8 km with the width ranging from 1 to 2 km. The geological formation consists of mudstone and sandstone. The length of the westernmost section of the island is about 3 km with the maximum width of about 1 km. The primary rock formation is limestone. As indicated by the color of water in Fig. 2c, the water depth on the southern side of the tombolo (Ton Sai Bay) is deeper than the northern side (Loh Dalam Bay). The field investigation documented very localized tsunami-induced damages along the coastline of the island. Figure 3a shows the degree of erosion induced by the tsunami along the coastline of the northern part of Loh Lana Bay and the huge boulders that were transported on land. A huge boulder with dimensions of 3m×3m×2m (Fig. 3b) was uplifted to the location marked as ‘A’ (Fig. 3a) which is also an outlet which allowed water surges to flow over land to the eastern side (the Sea Gypsy Village). An intact plastic bottle and some intact small pebbles supporting the huge boulder, suggest that it was not deposited there by rock all from the slopes above, but that it was transported to this location by tsunami wave action (since there is no evidence of crushing on the contact points). Judging from the size of the boulder, the tsunami’s water flow velocity must have been extremely high in this area (approximately 20m/s). Furthermore, the directional bending of the piers, confirmed that the tsunami flow was from west to east (Fig. 3c).

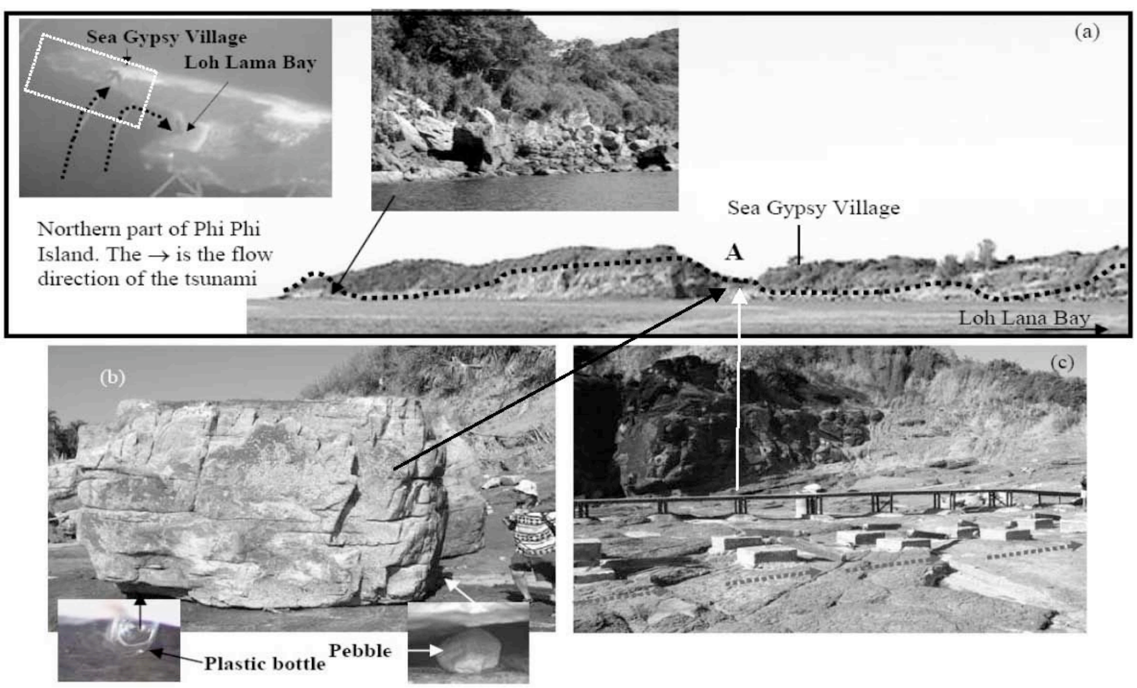


Fig. 3 (a) Non-uniform tsunami run-up height along the northern coastline of Loh Lana Bay. (b) Small photos showing transport of boulders by the tsunami with an undamaged plastic bottle and pebbles underneath the huge boulder. (c) Bent piers indicating tsunami flow direction.

Both north and south sides of the tombolo suffered extensive damage. Internet photos (Fig. 4) indicate that the tsunami came from the north side of the tombolo (Loh Dalam Bay, Figs. 4a & 5a). The run-up height reached the second floor of the hotel there (Fig. 4b) and overflowed the tombolo towards Ton Sai Bay (Figs.4c & 5a). It is believed that the higher run-up was the result of Loh Dalam bay's deeper bathymetry and coastal configuration. Figure 4c shows the tsunami wave retreating northward to the sea. The enlarged small photo at Fig. 4c shows debris floating in Ton Sai Bay. Eyewitnesses stated that tsunami waves approached the tombolo from both north and south directions. By measuring the scar on top of coconut trees there, the maximum tsunami run-up height was determined to range from 14 to 16 meters (Fig. 5b). Coral boulders with diameters ranging from 1-3 m were uplifted by the tsunami on the north side of the tombolo (Fig. 5c). Figure 5d shows a toppled 2-meter high statue on a pedestal. The steel bars connecting the statue and the stand were all bent in a SE direction, indicating that the stronger tsunami waves came from the north side of the tombolo.

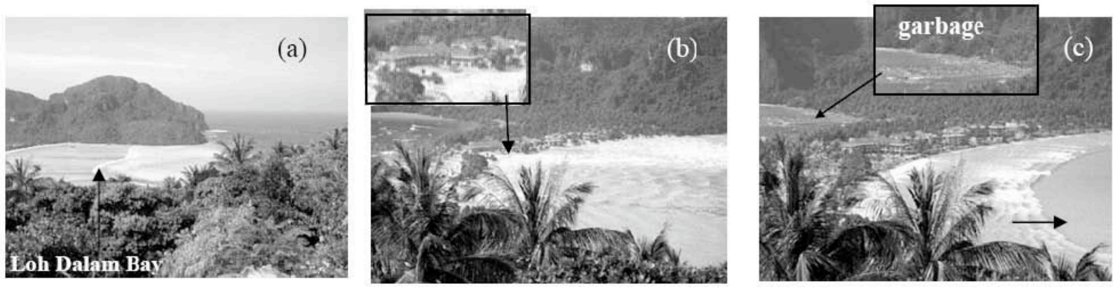


Fig. 4 (a) Tsunami approaching from the north side of tombolo (b) tsunami impacting the north side of tombolo and causing overflow, (c) wave retreating northward with lots of debris floating on the south side of the tombolo

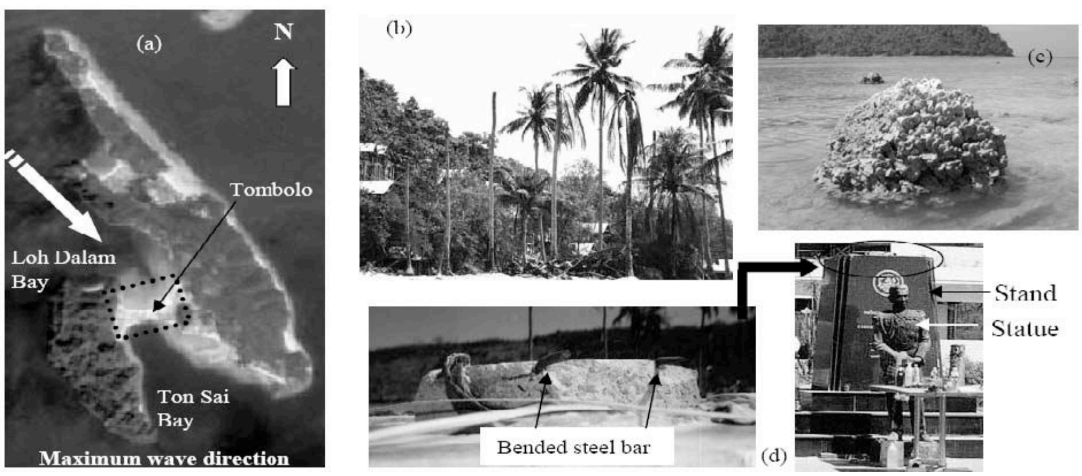


Fig. 5. Tsunami damage on north and south side of tombolo.

These observations raise the question as to why the island to the left of the tombolo was sheltered from tsunami surges. Why did the tsunami wave propagated around the island and impacted to a greater extent the tombolo from both north and south directions?

In fact, similar localized run-up of tsunami has been observed during other great tsunami events elsewhere. Hilo on the Island of Hawaii is the worse affected location every time a tsunami strikes. Weigel (1970) used the results of a physical hydraulic model (scaled 1:5,000) to demonstrate that edge waves (trapped waves traveling along the coastline caused by the superposition of the reflected tsunami with the incoming surges) is responsible for tsunami directional focusing effect there and for the highly localized tsunami run-up heights. The tsunami recorded at Hilo on February 8, 1963 traveled from the east and had a period of 16 minutes. The lines of "Mach stem" or "lines of trapped edge waves" were observed by filming the experiments. The wave run up heights depended on bathymetry and slope of the offshore region, on coastal morphology and on resonance (Wiegel, 1970). The generation mechanism of trapped edge waves was studied extensively to determine its effect on localized tsunami run-up along an irregular coastline (Wiegel, 1970; Dudley and Lee 1998, Bryant, 2001). The edge wave pattern can be duplicated in the laboratory by using a hydraulic model of 1:5,000 scale. Dudley and Lee (1998) reported that a physical model of Hilo harbor with horizontal scale of 1:600 and vertical scale of 1:200 had been used to model the tsunami. Our preliminary observations at Phi-Phi Island suggested that the edge wave phenomenon might be used to explain some of the field observations. Evidently, there were many complex wave reflections that interacted with the incoming trains of the tsunami, in a way that an edge wave was formed. The flow velocity of such edge wave was particularly high and may reflect what actually happened on Phi-Phi Island. Thus, the purpose of our study was to perform laboratory tests to simulate the propagation of the edge wave along the coastline of Phi-Phi Island and compare the results with data from field observations. The scale of the physical model that was used for this investigation was constrained by laboratory space limitations at the Hong Kong Polytechnic University. The model was designed in a way that the size of tsunami and its incoming direction could be adjusted as much as possible. The intent was to use parametric studies to examine the complex interactions created by the local bathymetry, the size and shape of the island and the tsunami wavelength. At the conclusion of the experiments it was determined that the modeling results not only provided good understanding of the effects of edge waves at Phi-Phi Island during the 2004 tsunami, but also provided some insight on the potential tsunami hazard for Hong Kong, where the irregular coastline is would be conducive to the formation of edge waves, if a tsunami strikes.

3. PHYSICAL MODELING AND EXPERIMENTAL SETUP

The physical model of Phi-Phi Island (Fig. 6a) was constructed from corrugated paperboards, each with a paper thickness of 0.6 mm. For a physical hydraulic model, it is normally impossible to have a 1-to-1 vertical and horizontal scale. Some kind of distortion of the vertical scale seems acceptable to avoid the effects of capillary rise and surface tension of the water. Previous experimental studies normally used a scale ratio h/v (horizontal scale/ vertical scale) ≤ 4, so that the distortion due to the scale effect can be negated (Whalin and Chatham, 1976). However, due to the limited space of the laboratory, an h/v ratio of 5 was used by this study with the horizontal scale being 1:2,500 and the vertical scale being 1:500 for the submerged portion of the model but remains at 1:2,500 scale for the portion above water level. The island was scaled down to about 3m in length and 1.5m in width. The whole model was fixed in a 6m×6m×0.3m (length×weight×height) lower steel tank (Fig. 6b).

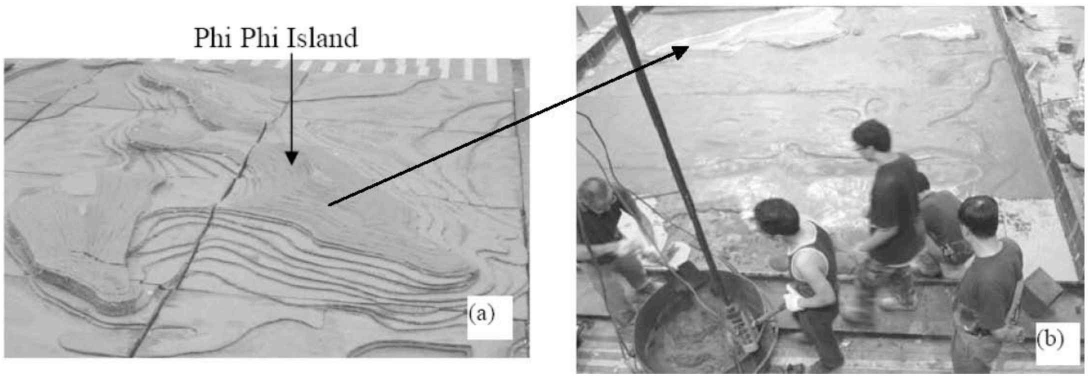
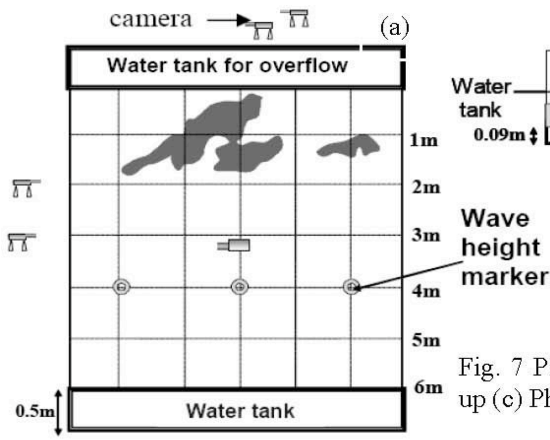


Fig. 6 (a) Model of Phi Phi Island, (b) Submerged portion of the model being covered with a layer of concrete (Model of the island fixed within a 6m×6m×0.3m steel tank).



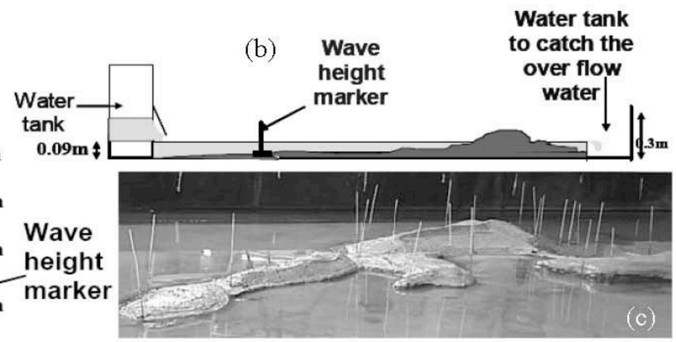


Fig. 7 Plane view (a) and section view (b) of the experimental set up (c) Ph Phi island with the bamboo markers

The physical model, including the island and the submerged portion, were covered by a layer of concrete. After the cement paste is hardened, Water was added to the tank to an approximate level of 90 mm. A separate water storage tank of 6m×0.5m×0.6m (called tsunami tank hereafter) was constructed to serve as the source of tsunami waves and was placed at the far end of the model (Fig.7). A gate was installed at the lower part of the tsunami tank for the sudden release of the water and the generation of simulated waves. The water tank was built on movable rollers outside the model so that the angle of tsunami direction could be adjusted. To prevent wave reflections from the two sides and the opposite wall of the model, a soft 60 mm thick water-absorbent material was mounted on all three sides with an overflow edge at the far end to prevent reflections from behind Phi-Phi Island replica. Wave height markers (Fig. 7a) and bamboo markers (Fig. 7c) were installed to measure the height of the waves and the run-up on the island. Additionally, five video cameras were installed at different locations to record the formation of edge waves and the maximum run-up in the model. Simulated waves were generated having heights varying form 30mm, 40mm and 50mm. Some of the results of our experimental observations are given in the next section.

4. THE EFFECT OF COASTAL MORPHOLOGY ON EDGE WAVE PROPAGATION

Figure 8 shows a sequence of photographs taken from the top of the model, illustrating the wave propagation toward the island. For this particular experiment, the water depth in the tsunami tank was 40 mm with an orientation of N0.0°. Once the gate was opened, a line of water was generated and propagated toward the island. Initially observed was the formation of a zone of water level depression (or water draw back) ahead of the first crest, which agreed with observations in Thailand that the sea retreated prior to arrival of the first tsunami wave (see elongation of light reflection before the wave in Fig. 8). The same phenomenon has been observed with many tsunamis in the past – specifically that a wave of higher crest is followed by a number smaller undulations. A mathematical wave called soliton has a similar waveform, similar to a tsunami. Another observation was the reduction of wave speed due to changes in bathymetry. The waves refracted with changes of water depth and coastal configuration. At the tombolo the water first retreated, then rose drastically. At wave marker (2 m away form the water tank), the average wave height was about 14 mm above mean water level, while the wave run up height at the tombolo was 21 mm at the south side and 30mm at the north side. The wavelength was about 0.45 m. The wave speed, at 1 m away from the tsunami tank, was 1.13 m/sec and it decreased to 0.73 m/sec at 2.5m from the tsunami tank. As illustrated by the modeling study and presented in detail in the next section, depth of water and coastal morphology are critical factors in the resulting tsunami run up.

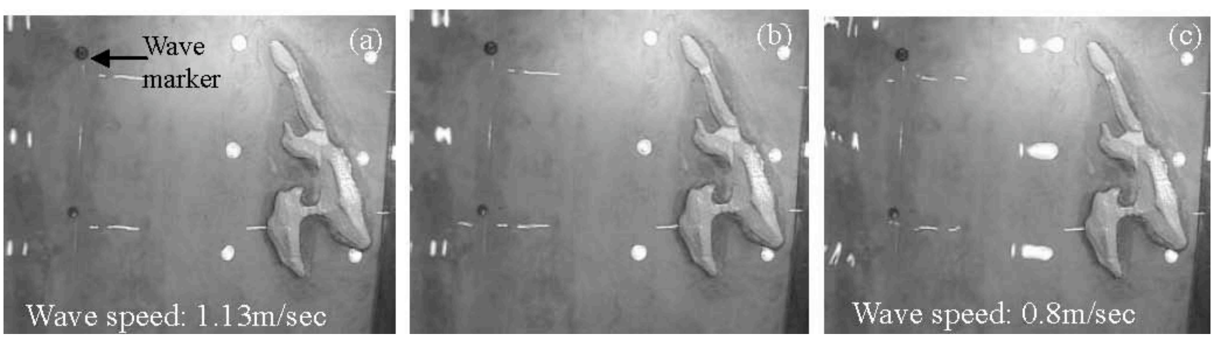


Fig. 8 Wave propagation and interaction with coastal morphology in the generation of edge waves

5.1. Wave attack on the northern coastline of Loh Lana Bay

The topography of the northern side of Phi-Phi Island consists of a flat land 'A' in-between two small hills (Fig.9a and 9d). When wave propagates toward this area, it was observed that there is water overflow to the other side of the island (Fig. 9a). As a result, this low-lying area became an outlet for the tsunami surge and drew adjacent water through it (Fig 9b). The water wave speed in this area could not be recorded but the recorded run-up height was 33 mm above still water level and was higher than what was measured at the tombolo (to be further discussed). This observation provides an explanation why the erosion of the coastline on this flatland of Phi-Phi Island is higher than other parts along the northern coastline (Fig. 9d). In addition to the water overflow, part of the wave (edge wave, see Fig. 9b) traveled along the coastline of the island around the northern tip (see the small photo of Fig. 9b) moving downward along the backside of the island. On the right side of the flat land 'A', a reflected wave (edge wave) was observed traveling along the coastline and moving towards to the southern bay (Fig. 9c). However, since there is no outlet for the water there, the surge reflected back and interacted with the incoming edge waves to form a highly non-uniform and localized run-up height along the northern coastline. This also explains what we actually observed along the northern coastline of Phi-Phi Island. Therefore, the experiments provided useful insight of what happened in this area when the tsunami of December 26, 2004 struck.

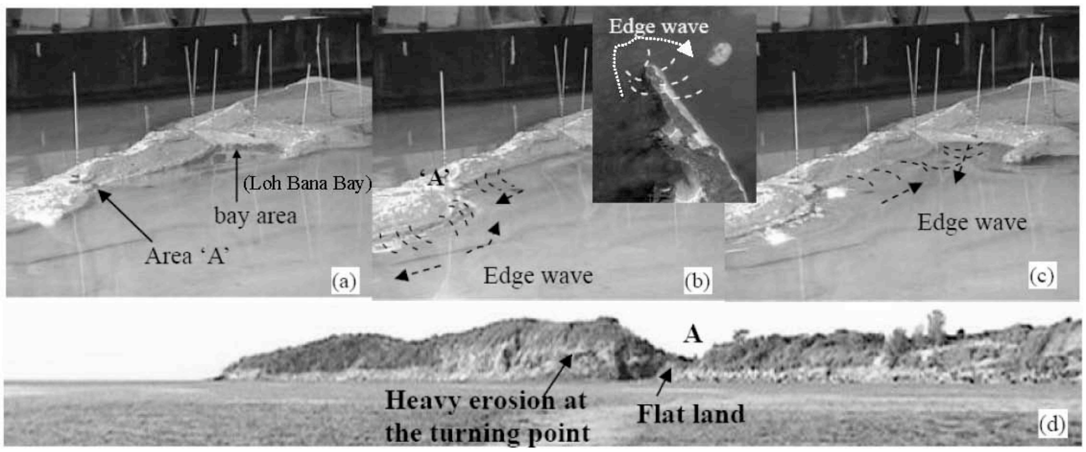


Fig. 9 Illustration showing tsunami wave attack on northern area of the model of Phi-Phi Island

5.2. Wave attack on the Northern Side of the Tombolo (Loh Dalam Bay)

It was observed that when the wave propagated towards Loh Dakam Bay, part of the wave reflected at area B and C (Fig. 10a) while part of the wave moved directly into the bay area. It was observed that at area B, the edge wave moved along the coastline propagating downward to the bay area (Fig. 11b). At the same time the reflected wave (or edge wave) moved along the coastline of area C also propagated toward the bay area (Fig. 11c). As a result, three sources of water flow into the bay area caused the 30 mm run-up height at the north side of the tombolo.

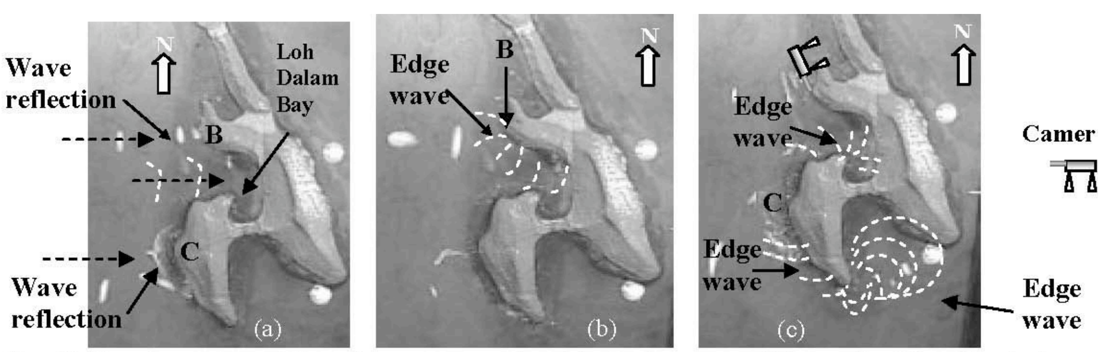


Fig. 10 The plane view of the edge waves moving into the bay area of the north side of tombolo.

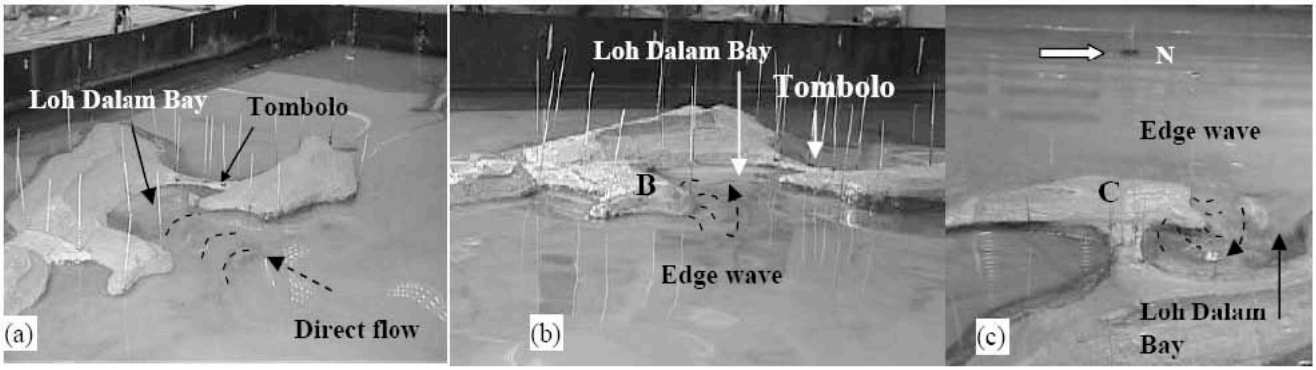


Fig. 11 Photos showing the sources of water from the northern side of the tombolo (Loh Dalam Bay)

To give a clearer picture, three more photos of the Loh Dalam Bay area (Figs. 11a-c) were taken from different angles (locations of cameras shown in Fig. 11c). It was clear that water was coming from three different sources and directions (direct flow, edge wave moving along the coastline of area B and C, respectively). The laboratory observations show that the surge coming from the north of the tombolo was much higher than that from the south, which also agree with field observations that all the damages were caused by surges from the north. The hydraulic model experiments provided a simple reconstruction of what actually happen at Phi-Phi Island and explain why a tombolo which is not directly facing the incoming tsunami, suffered such heavy damage and casualties. It also demonstrates the importance of edge waves on enhancing tsunami run-up.

5.3 Wave attack on the South Side of the tombolo

There is no direct flow source for the south side of the tombolo, since the south bay is sheltered from direct tsunami impact. However, the experiments also show that edge waves were formed and traveled around the left headland. More specifically, when the simulated tsunami wave propagated towards to southern end of the island, it was observed that edge waves were formed that continued to move along the coastline towards to the tombolo (Fig. 11c). Three more photos of the tombolo area taken from different angles are shown in Fig. 13. Figure 13a was taken from the eastern camera while Figs. 13b and 13c were taken form the northern camera. It was observed that edge wave turned around the southern tip of Phi-Phi Island (Fig. 13a) and propagated across to the bay towards the southern side of the other island, with wave fronts nearly parallel to the tombolo (Figs. 13b & c). As a result, the wave arrival time from the south side of tombolo is later than that from the north side. Figure 13c clearly shows that when the surges overflowed the tombolo from the north, the edge wave from the south side was still advancing toward the tombolo. The difference in arrival time on the two sides was about 2.5 sec. Because the source of water from the south was only from the edge wave, the run-up height was only 21 mm. The field observations were in full agreement with the conclusions derived form the hydraulic model experiments. As shown in Figs. 4b and 4c, when the tsunami approached from the north side of the tombolo, the sea on the south side was calm. The debris on the south side resulted by the overflow of water from the north side. That is, wave reached first the north side of the tombolo and the run-up was higher.

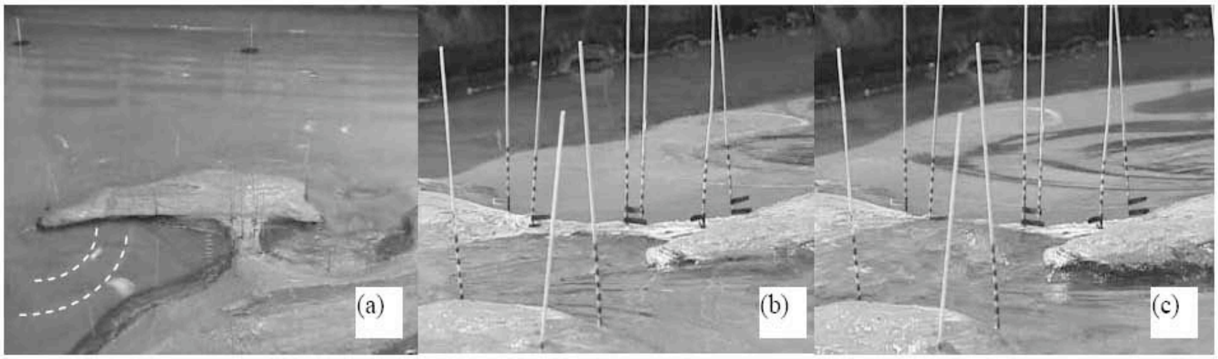


Fig. 12 (a) Edge wage propagation along the coastline, (b) and (c) show the flooding and overflow at the north side of the tombolo while the edge wave propagation from the south side was still going on.

Table 1 summarizes the run-up heights from the model experiments for different initial water depth in the tsunami tank (30mm to 50mm) and different directional orientations (zero to twenty degrees from west-east direction). In general the behavior of edge wave propagation is more or less the same, except for the overflow behavior. For larger initial volume of water displaced (i.e. deeper water in the tsunami tank), more overflow and higher run-up height were observed. All wavelength, crest heights of and wave propagation speeds of the experiments are listed in Table 1. The wave speed, wave height and wavelength clearly increase with the amount of the water displaced. For all of the lab experiments, the run-up heights at the tombolo from north surges were larger than the ones from the south.

Table 1 Lab results of simulated (scaled down) tsunami run-up heights and wavelengths under different water depth conditions.

Water Depth (mm)	South side of tombolo Run up height (mm)	North side of tombolo Run up height (mm)	Wave Length (m)	Wave Height (mm)	Wave speed (m/sec) Measured at 2 m Away from water tank
30	18	28	0.3	8-9	0.9
40	21	30	0.45	14-15	1.13
50	23	33	0.5	20-22	1.18

6. CONCULSIONS

These experimental simulations of edge waves along Phi-Phi Island using a physical hydraulic model had a good correlation with the field observations. The modeling simulations showed that edge waves were formed along the coastline of Phi-Phi Island The formation and specific characteristics of the edge waves that were formed showed a dependence on water depths and initial directional orientation. The experimental observations helped explain that the damages on the tombolo of Phi-Phi Island were caused from surges from the north and not from the south. Also, the experiments showed that areas of low elevation along the northern coastline of Phi-Phi Island became an outlet of tsunami surges, which also agrees with observations in the field. The high flow velocity of the tsunami is evident from the huge boulders that were carried on land by strong surges near the outlet. The results of the study provided a better understanding on the formation of edge waves and the potential impact that a tsunami in Hong Kong could have.

ACKNOWLEDGEMENT

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