Experimental study on edge wave effect inducing by tsunami at Phi-Phi Island (Thailand)

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ABSTRACT :

This study presents edge wave effect along Phi-Phi Island (Thailand) experimentally and compares the laboratory observations with the field trip. The model is made by paper boards and covered with a layer of cement-sand mixing. The physical model of Phi-Phi island has a vertical scale of 1:500 and a horizontal scale of 1:2500. The whole physical model was fixed in a 6m×6m steel tank. Waves are created by releasing the water from a long steel rectangular water tank (6m×0.5m×0.6m) by suddenly opening a gate. The initial water level in the water tank can be adjusted so as to create tsunami surges of various sizes. The experimental observations focus on the effect of edge waves, the run up height and the arrival time of tsunami. The results can explain why the damages on the tombolo are most devastating. It was found that the edge wave propagation is strongly affected by the size and shape of the island. The run up height at tombolo, wave height and wave speed were examined. These experimental observations provide a valuable bench results for calibrating and validating numerical models for tsunami waves.

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

. INTRODUCTION

On December 26, 2004, the worst tsunami ever occurred in South Asia, it was induced by a huge earthquake of magnitude of 9.0 just southwest of Sumatra of Indonesia (Fig.1a). This tsunami caused a total death toll of over two hundred twenty thousands. The death tolls are highest in Indonesia, Sri Lanka, India and Thailand. The earthquake was believed driven by relative movement between the Australian plate and Eurasian tectonic plates (Fig. 1b). The Australian plate is still very active and causes another recent earthquake in Pakistan in Oct. 2005. Hong Kong is located on the Eurasian plate, which is next to the Philippine plate. Earthquakes and volcanic activities are found along the boundary between the Philippine and Eurasian plates. Thus, it is not unlikely that coastline of South China Sea, including Hong Kong, may be at risk from future potential tsunami events.
A special research fund was awarded from the the Faculty for estimating the potential tsunami risk of Hong Kong and China. A 4-day tsunami reconnaissance trip to Phuket and Phi-Phi Island of Thailand was held from Feb 4-7, 2005 to study the tsunami damages on the coastline and island (Fig.2). In this study, we focus on the experimental model testing on wave effect caused by tsunami at Phi Phi Island and compare with what we observed in the field trip. It is believed that the results not only provide the knowledge of edge wave but also provide some insight on the potential tsunami in Hong Kong. This paper is divided into three sections. First, a briefly observations on edge wave inducing by tsunami at Phi Phi Island and the pervious studies of physical hydraulic model testing on edge wave problem is presented, followed by the details of physical model and testing edge wave effects on Phi Phi Island are discussed.

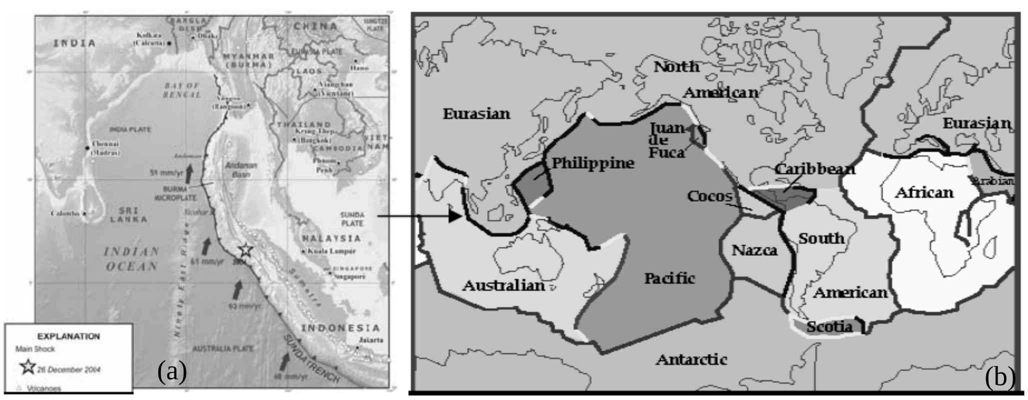


Figure 1 (a) Earthquake at Indonesia along the boundary of Australian plate; (b) The tectonic plates of the world

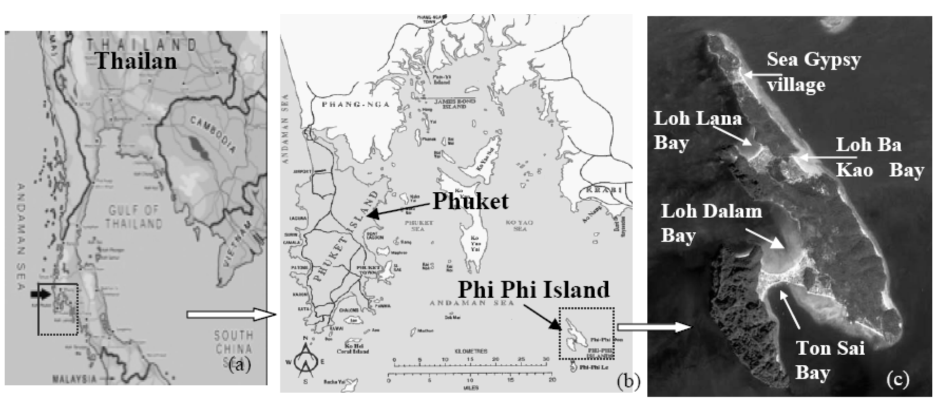


Fig.2 Phuket and Phi Phi Island

2. FIELD RECONNAISSANCE TRIP TO PHI PHI ISLAND

Phi-Phi Island is composed by two small narrow islands connected by a tombolo as shown in Figs. 2c. The orientation of both islands is roughly NNW. The length of the eastern island is about 8 km with the width of 1

to 2 km. The geological formation of the island consists of mudstone and sandstone. The length of the western island is about 3 km with the maximum width of about 1 km. The geology condition of the island is limestone. As shown by the color of the 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). From our observations made in the field reconnaissance trip, very localized tsunami-induced damages have been observed along the coastline of Phi-Phi Island.
Figure 3a shows the erosion induced by tsunami along the coastline of the northern part of Loh Lana Bay and huge boulders were transported on land. A huge boulder of 3m×3m×2m (Fig. 3b) was up lift onto the location marked as ‘A’ (Fig. 3a) which is also an outlet allowing water surges overflowing the land to the eastern side (the Sea Gypsy Village). An intact plastic bottle and some intact small pebbles supporting the huge boulder suggests that the boulder did not land there by rock fall from slopes above, instead it was transported by water (since there is no evidence of crushing on the contact points). Judge from the size of the boulder being uplift on land, the flow velocity must be extremely high in this area (say in the order 20m/s). Furthermore, piers were bended to one direction, confirming that the tsunami flow was from west to east (Fig. 3c).

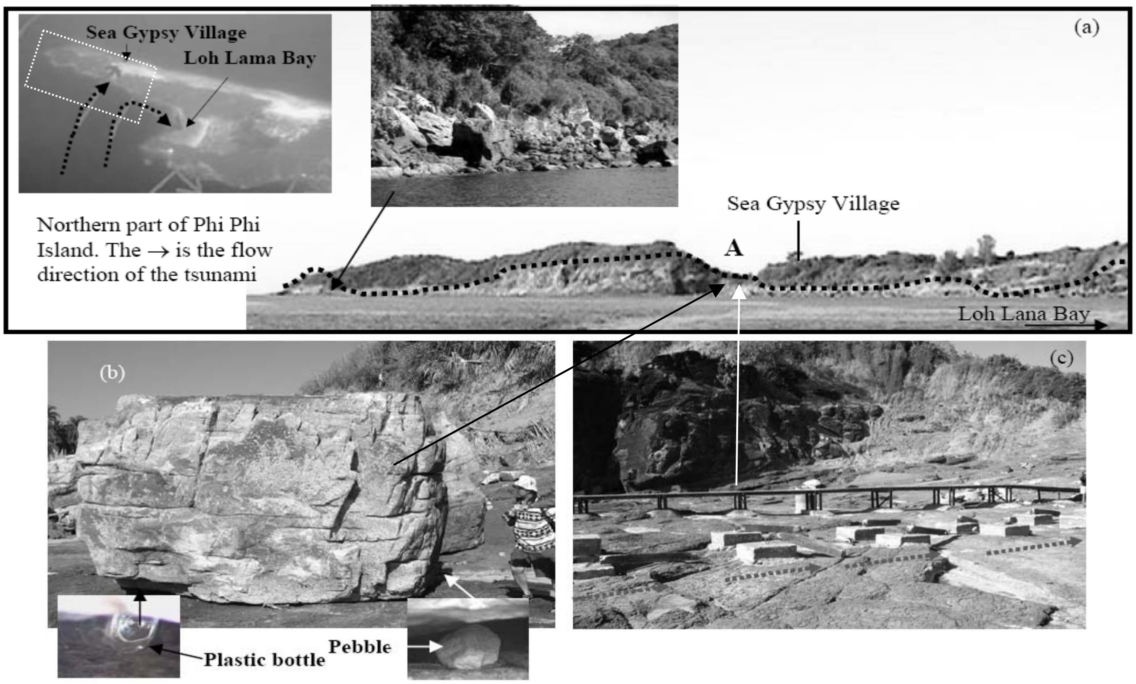


Fig. 3 (a) Non-uniform run-up height along the northern coastline of Loh Lana Bay. (b) Small photos show boulders transported by tsunami while plastic bottle and small pebble underneath the huge boulder without damage. (c) Piers are bended to one direction representing flow direction of the tsunami

For the damages on the tombolo, both the south and north sides of the tombolo suffered heavy damages. According to the photos downloaded from the Website (Fig. 4), tsunami surge came from the north side of the tombolo (Loh Dalam Bay, Figs. 4a & 5a). The run-up height of the surge reached the second floor of the hotel (Fig. 4b) and overflowed the tombolo towards to Ton Sai Bay (Figs.4c & 5a). It is speculated that this is resulted from the bathymetry and shape of the Loh Dalam bay. Figure 4c shows the wave retreating northward to the sea. The enlarged small photo at Fig. 4c shows debris floating on the Ton Sai Bay. It was told by the residents of the tombolo that the tsunami surge was not only to attack on the northern side but also on the southern side of the tombolo. The run-up height of southern side was less than that of the northern side. By measuring the scar on the top of the coconut trees on the tombolo, the maximum run-up height of water may be up to 14m to 16m (Fig. 5b). Coral with diameter of 1-3 m were uplift by the tsunami surges on north of the tombolo (Fig. 5c). Figure 5d shows a statue on a 2 m high stand was overthrown. The steel bars connecting the statue and the stand were all bended to SE direction, indicating that the strongest surge of water came from the north side of the tombolo.

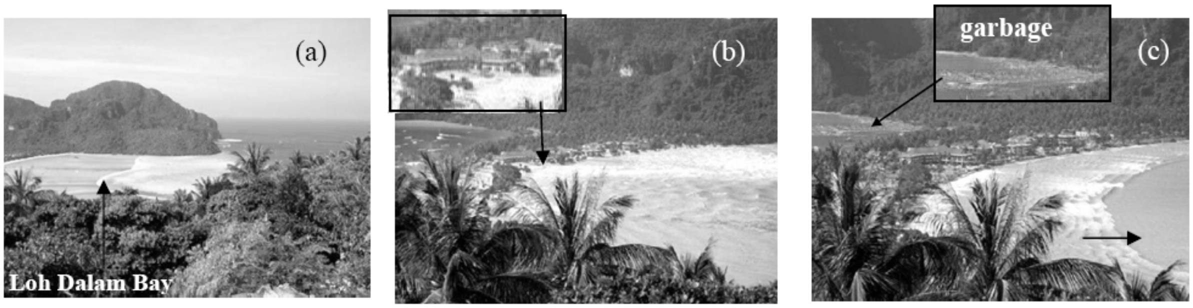


Fig. 4 (a) Tsunami approaching from north side of tombolo (b) tsunami attacking north side of tombolo and causing overflow, (c) wave retreating northward to sea and lots of debris floating on south side of the tombolo

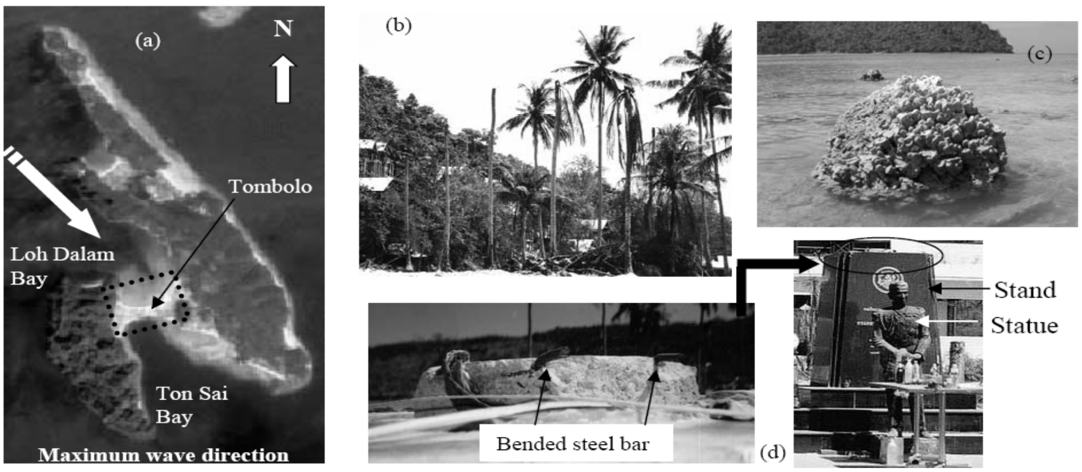


Fig. 5 Damages induced by the tsunami on both north and south side of tombolo.

It is natural to ask why the island to the left of the tombolo shelter it from the tsunami surges. Why the tsunami wave seems to turn around the island and surges from both north and south of the tombolo? In fact, similar localized run-up of tsunami has been observed during other great tsunami events. Hilo of Hawaii is the spot suffering the hardest hit every time when a tsunami hit Hawaii. Weigel (1970) used the results of physical hydraulic model of scale 1:5,000 to demonstrate that edge wave (a trapped wave traveling along the coastline caused by superposition of the reflected tsunami with those incoming surges) is responsible for the changing direction of tsunami locally and for the highly localized run-up. The mode is for original tsunami recorded at Hilo on February 8, 1963, and it was of a period of 16 minutes. The original tsunami traveled from the east. The lines of "Mach stem" or "lines of trapped edge waves" was observed from film of the experiments. In additions, the run up height of water depend upon the offshore hydrography, slope and configuration of the shore and on resonance (Wiegel, 1970). The mechanism of such trapped edge waves have been studied intensively because of its importance on localized run-up of tsunami along irregular coastline (Wiegel, 1970; Dudley and Lee 1998, Bryant, 2001). The edge wave pattern can be duplicated in the laboratory by using hydraulic model although the scale is 1:5,000. Dudley and Lee (1998) reported that a physical model of Hilo harbour on the Big Island of Hawaii of horizontal scale of 1:600 and vertical scale of 1:200 has been used to model effect of tsunami.

Our preliminary observation at Phi-Phi Island suggests that edge wave phenomenon may be used to explain some of the field observations. Evidently, there are very complex wave reflections interacting with the incoming trains of surges in such a way that the edge wave is formed. The flow velocity of such edge wave is particular high and may reflect what have happened on Phi-Phi Island. Thus, the purpose of our study is to perform laboratory tests studying edge wave traveling along the coastline of Phi-Phi Island (Thailand) and compares the observation with field evidences. The choice for the scale of the present physical model is constrained by laboratory space limitation at the Hong Kong Polytechnic of University. The model is designed in a way that the size of tsunami and incoming orientation can be adjusted as far as possible. The complex interactions between the bathymetry of the sea, the size and shape of the island, and the wavelength of the tsunami will be examined through parametric studies. It is believed that the results not only provide the knowledge of edge wave at Phi-Phi Island during the 2004 tsunami but also provide some insight on the potential tsunami hazard in Hong Kong where the irregular coastline is conducive to the formation of edge waves when tsunami hit.

3. PHYSICAL MODELING AND EXPERIMENTAL SETUP

The physical model of the island is made by corrugated paper boards (each thickness of the paper is 0.6 mm as shown in Fig. 6a). For laboratory physical hydraulic models, it is normally impossible to have a 1-to-1 vertical and horizontal scale. Some kind of distortion of the vertical scale (comparing to the horizontal one) seems acceptable to avoid the effects of capillary rise and surface tension of the water. Pervious 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 pace of the laboratory in our University, h/v of 5 is used in this study where the horizontal scale is 1:2,500 while the vertical scale is 1:500 for bathymetry but remains 1:2,500 for landscape 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).

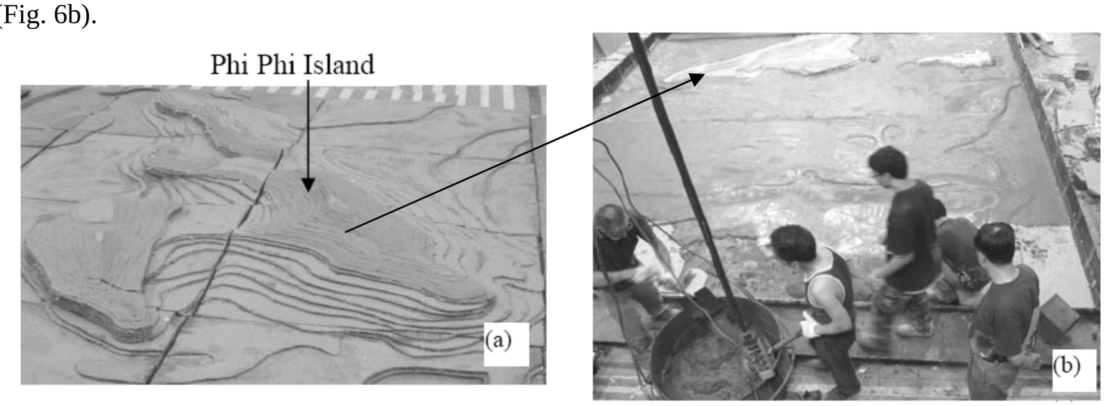
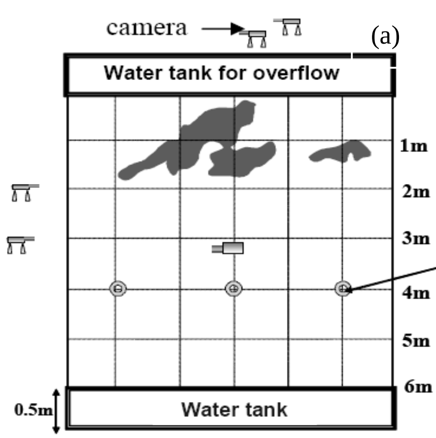


Fig. 6 (a) The model of Phi Phi Island, (b) the Phi Phi island and the bathymetry covering by a layer of mixture of the cement sand. The whole mode is fixed in a 6m×6m×0.3m steel tank.



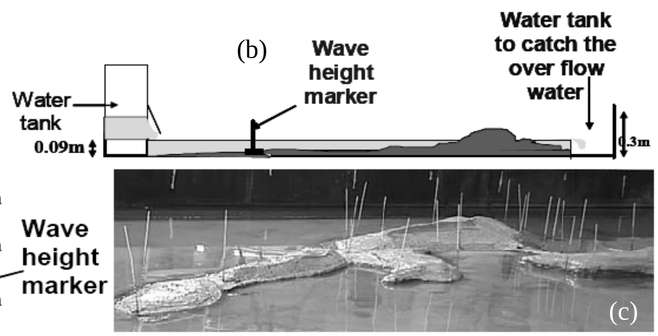


Fig. 7 Plane view (a) and section view (b) of the experimental set up (c) Ph Phi island with the bamboo markers

The physical model including the island and the bathymetry was covered by a layer of cement-sand paste. After the cement paste is hardened, water was filled into the tank to a water depth of about 90 mm. A separate water storage tank of 6m×0.5m×0.6m (called tsunami tank hereafter) was manufactured to provide the source of tsunami waves and it was placed at the far end of the lower tank (see Fig.7). A gate was installed at the lower part of the tsunami tank for releasing the water and simulating the effect of tsunami. The water tank was built on movable rollers outside the model so that the angle of tsunami attacks can be adjusted. To prevent the wave reflections from the two sides of the lower water tank and from the other end of the lower tank, a soft and water absorbent material of 60 mm thick was mounted on the side edges of the lower tank whereas a water-overflow edge is made at the far end so that surges will not be reflected from behind the Phi-Phi Island. Wave height markers (Fig. 7a) and bamboo markers (Fig. 7c) were installed to measure the height of wave and the run-up on the island Five video cameras were set at different locations to capture the edge waves and maximum run-up. In our simulations, the water depth of attack of the tsunami tank vary form 30mm, 40mm and 50mm, respectively. Some of the results of our experimental observations are reported in the next section.

4. THE EFFECT OF SHAPE OF COASTLINE ON EDGE WAVE PROPAGATION

Figure 8 shows a sequence of photographs taken from the top to illustrate the wave propagation toward the island. For this particular experiment, the water depth in tsunami tank is 40 mm with a orientation of N0°. Once the gate was opened, a line of water was generated and propagating toward the island. It was observed that a water depression zone (or water draw back) was formed ahead of the first crest of the wave, and this agrees with the fact that sea retreat was observed in Thailand before the tsunami hit (see the elongation of light reflection before the wave in Fig. 8). Actually the same phenomenon has been observed in many previous tsunami events. It was observed that a wave of larger crest following by a number smaller undulations. A mathematical wave called soliton has a similar wave form and may be capable of modeling the tsunami surge. We also observed that the wave speed slows down due to the change of the bathymetry. The surge was diverted by the change of bathymetry and by the shape of the coastline, so that water at the tombolo first retreated and rised drastically. According to the wave marker (2 m away form the water tank), the average wave height is about 14 mm above the mean water level, while the wave run up height at the tombolo is 21 mm at the south side and 30mm at the north side of the tombolo. The wave length is about 0.45 m. The wave speed at 1 m away from the tsunami tank was1.13 m/sec and it decreases to 0.73 m/sec at 2.5m from the tsunami tank. When wave attacks on to the coast, the local water run-up is highly sensitive to the shape and bathymetry of the coastline. The details are presented in the next section.

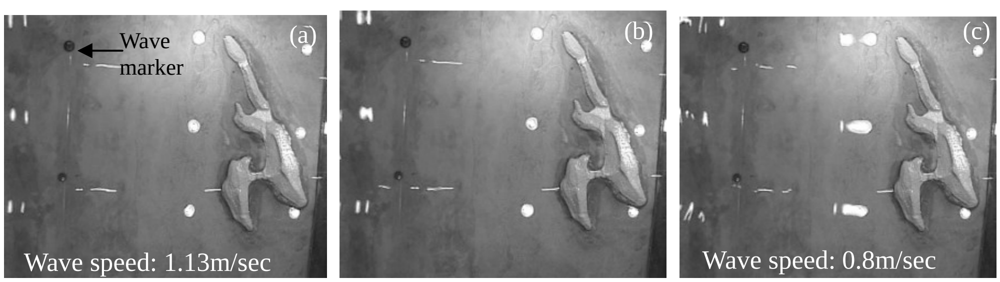


Fig. 8 Wave propagation process and the effect of shape coastline on edge wave

5.1. Wave attacking 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 the two small hills (Fig.9a and 9d). When wave propagates toward this area, it was observed that water overflows this area to the other side of the island (Fig. 9a). As the results, this lower area became an outlet for the tsunami surge and drew adjacent water pass through it (Fig 9b). The water wave speed in this area cannot be recorded but large amount of water overflow here as the run-up height was recorded of 33 mm above the still water level. This run-up height is higher than that of the tombolo area (to be discussed in next section). It provides an explanation that the erosion of the coastline left of this flatland on Phi-Phi Island is higher than other parts along the northern coastline (Fig. 9d). Besides the overflow water, 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 back side of the island. On the right side of the flat land ‘A’, reflected wave (edge wave) was observed to travel along the coastline moving towards to the southern bay (Fig. 9c). However, since there is no outlet of water there, the surge was 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 observed along the northern coastline of Phi-Phi Island. Therefore, the experiments provide useful insight of what had happened there on December 26, 2004.

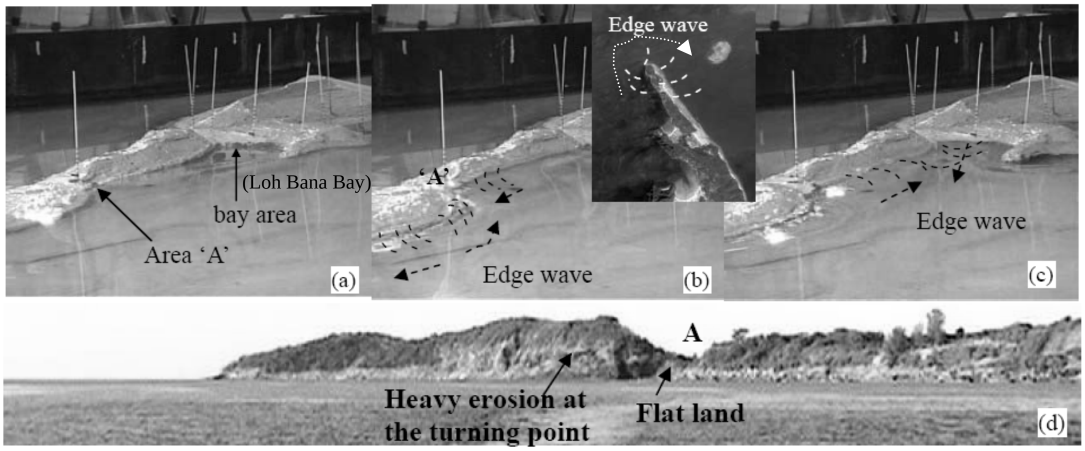


Fig. 9 Illustration showing the wave attacking on the northern area of the model of the Phi-Phi Island

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

It was observed that when wave propagated towards to the Loh Dakam Bay, part of wave reflected at area B and C (Fig. 10a) while part of wave moved into the bay area directly. It was observed that at area B, edge wave moved along the coastline propagated 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 and caused 30 mm run-up height of the water at the north side of the tombolo.

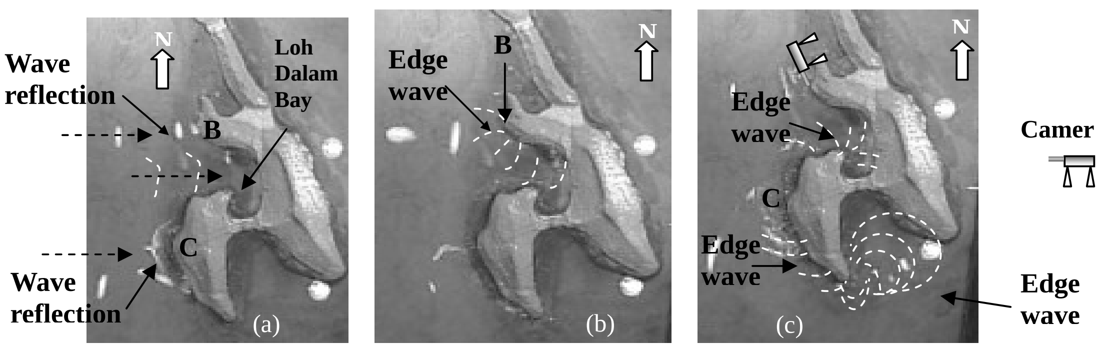


Fig. 10 The plane view of the edge waves moving into the bay area of the north side of tombolo.

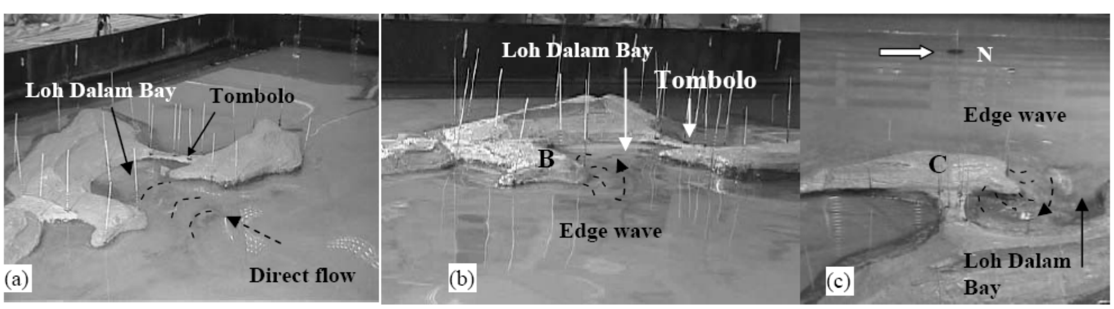


Fig. 11 Photographs showing the sources of water from the northern side of the tombolo (Loh Dalam Bay)

To give a clearer picture, three more photos of the Loh Dalam Bay area (Figs. 11a-c) were given from different capture angles (the locations of the cameras were shown in Fig. 11c). It was clear to show that sources of water are coming from three different directions (direct flow, edge wave moving along the coastline of area B and C, respectively). Our laboratory observations show that the surge coming from the north of the tombolo is much higher than those from the south, and this agrees with our field observation that all damages were caused by surges from the north. These experiments provide a simple reconstruction of what actually happen at Phi-Phi Island and explained why a tombolo which is not directly facing the incoming tsunami suffered such heavy damages and casualties. It also demonstrates the importance of edge waves on tsunami run-up and that we should not estimate the tsunami effect by “common sense” and neglecting the important phenomenon of edge waves.

5.3 Wave attacking on the South Side of Tombolo

For the south side of tombolo, there is no direct flow source since the south bay is sheltered from direct hit of surges. But experiments also show that edge waves were formed and traveled around the left headland. More specifically, when the wave propagated towards to southern end of the island, it was observed that edge waves were formed, moved along the coastline, and propagated towards to the tombolo (Fig. 11c). Three more photos of tombolo area taken from different angles were given in Fig. 13. Figure 13a was taken form 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 to the southern side of the other island with wave fronts nearly parallel to the tombolo (Figs. 13b & c). As the result, the wave arrival time from the south side of tombolo is later than that from the north side of tombolo. Figure 13c clearly shows that when the surges overflow the tombolo from the north, the edge wave from south side is still propagating toward the tombolo. The arrival time difference between the two sides is about 2.5 sec. Because the water source from the south came form the edge wave only, the run-up height is only 21 mm from the south surges. The observation form our field trip supported the conclusions from of our experiments. As referring the Figs. 4b and 4c, when tsunami attacked from the north side of tombolo, the sea of south side is calm. The debris on the south side was formed by the overflow of water form the north side. That is, water reached from the north side of the tomobolo first and the run-up is higher.

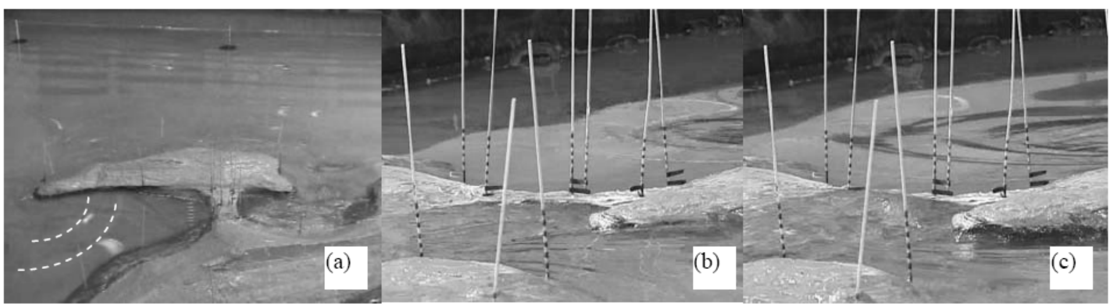


Fig. 12 (a) Edge wage propagation along coastline, (b) and (c) showing the flooding and overflow at the north side of tombolo while the edge wave form south side still going on.

Table 1 shows the run-up heights of our experiments for different initial water depth in the tsunami tank (30mm to 50mm) and different attacking 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 a larger initial volume of water displaced (i.e. deeper water in the tsunami tank), more overflow and a higher run-up height were observed. All the wave length, height of crest, and speed of our experiments were listed in Table 1. The wave speed, wave height and wave length clearly increases with the amount of the water displaced of the initial water depth in the tsunami tank. For all of experiments, the run-up heights at the tombolo from north surges are larger than the ones from the south.

Table 1 The running up of water height and wave length under different water depth condition

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

This study presents results of experimental simulations of edge waves along Phi-Phi Island using a physical hydraulic model and compares them with what we have observed in the field trip. The physical model uses 1:500 for vertical scale and 1:2500 for horizontal scale. The physical model of Phi-Phi Island is then fixed into a 6 m × 6 m water tank (called base tank) with the scaled bathymetry of the nearby waters using cement-sand paste. The maximum water depth in the tank is about 90 mm. Tsunami wave is created by releasing water suddenly from a long rectangular water tank (called the tsunami tank). The water depth in the tsunami tank can be adjusted and the incoming orientation of the tsunami wave can also be changed slightly since the tsunami tank is supported on rollers. Experimental simulations show that edge waves were formed along the coastline of the Phi-Phi Island model. The characteristics of the edge waves depend on the water depth in the tsunami tank and on the incoming direction of the tsunami surges. The experimental observations can also be used to explain why the damages on the tombolo of the Phi-Phi Island were caused from surges from the north, not from the south. Experiments also shows that a location of a lower ground along the northern coastline of Phi-Phi Island becomes an outlet of the tsunami surges, and this agrees with our field observation. The high flow velocity is evident from the huge boulders carried on land by the surges near the outlet. It is believed that our results not only provide the knowledge of edge wave but also provide some insight on the potential tsunami in Hong.

ACKNOWLEDGEMENT

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