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Protection from Tsunami Waves?

Experimental study on the effect of underwater barrier on tsunami waves

This paper summarizes the results of a research for finding a solution to reduce the destructive power of a tsunami when approaching a shoreline. Tsunami waves were generated in a tank with a deep-water part and a shore. The wave speed and the fluid particle velocity were measured with and without an underwater barrier. The results show that the barrier reduces the fluid particle velocity up to 47 % and consequently the energy of a tsunami.

1 Introduction

On December 26, 2004, the world witnessed one of the historically worst natural disasters. An earthquake with a magnitude of 9.15 occurred offshore Indonesia. The earthquake resulted in a tsunami which struck most of the countries surrounding the Indian Ocean, and killed more than 200 000 people [9]. This tragic event inspired this investigation.

By studying the information of the coast of Nicaragua after the tsunami in 1992, Synolakis et al. (1995) [11] observed that the highest levels of damage along a particular stretch of beach were located directly landward of a reef opening used for boat traffic. It was postulated that the reef behaved like a tunnel focusing the tsunami wave. Along neighboring beaches with intact reefs, the tsunami had a minor intensity. Earlier analytical studies carried out by Kanoglu and Synolakis (1998) [5] had shown found that small-scale bathymetry changes do impact the runup. A survey team in Sri Lanka inferred from observations of the recent Indian Ocean tsunami that reef and dune breaks lead to locally increased tsunami impact [7]).

Chang et al. (2001) [3] measured particle velocity using the PIV (Particle Image Velocimetry) method in the vicinity of a submerged rectangular obstacle. The generation, evolution and dissipation of vortices were investigated. Through these experiments these researchers investigated the interaction between a submerged rectangular obstacle and cnoidal waves and presented a numerical model. Lin et al. (2006) [6] studied experimentally the time-dependent characteristics of vortex structure induced by a solitary wave propagating over a submerged rectangular dike. Three flow visualization techniques were deployed. A relatively large number of vortices and complicated flow pattern was observed in these experiments. Lynett (2007) [8] employed a numerical technique to investigate how shallow water obstacles affect the runup and overland flow velocities of nonlinear long waves.

The purpose of the present paper was to study and evaluate the effect of an underwater barrier on reducing the destructiveness of a tsunami. It is a fact that it is the fluid particle velocity that governs the power of a wave; therefore the physical properties of a tsunami wave have been discussed in this article. The changes of the wave speed and the fluid particle velocity from the deep water to the shore

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were investigated. These parameters were calculated both by using theoretical formulas and an experimental approach. The main focus of the laboratory investigation was to examine how an underwater barrier placed near the shore affects the tsunami propagation. Since the behavior of a tsunami wave in deep ocean is not of practical interest, the experiment has mainly been focused on a tsunami propagating towards the shore.

2 Theoretical Background

Tsunami, meaning "harbor-wave" in Japanese, is a series of large waves with extremely large wavelengths. The waves are usually generated by a significant and impulsive undersea disturbance, for example by landslides, earthquakes or volcanoes (Fig 1). This causes a sudden displacement of a large water volume and generates a tsunami wave.

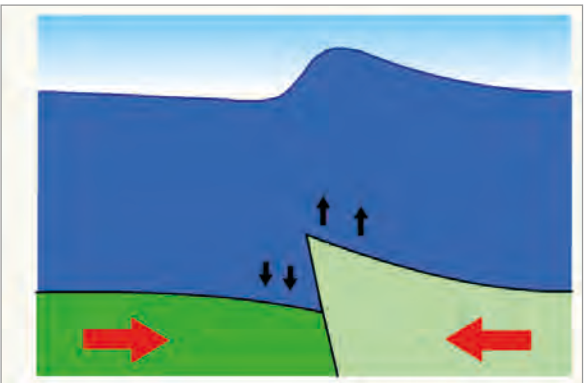


Figure 1: In the case of earthquake the sudden vertical displacement of the water disturbs the ocean surface and generates a tsunami. An earthquake in subduction zone with a Richter magnitude exceeding 7.5 can produce a destructive tsunami.

2.1 Tsunami wave properties

Tsunami waves travel outward as a water column stretched from the water surface to the sea bottom in all directions away from the generation source. The period of the tsunami wave may range from 5 to 90 minutes [10]. In the open ocean the wave amplitude may vary from only a few centimeters to a meter or more, and the wavelength may even be two hundred kilometers, which is many times greater than the ocean depth. Thus, tsunami behaves as a shallow-water wave, i. e. the relative water depth h/L is less than 1/20 (where L and h denotes the wavelength and water depth respectively).

The deeper the water, the greater is the speed of tsunami waves. For example, in deep open ocean, where the typical water depth is about 4-5 km, the tsunami wave speed is as much as 800 km/h. As a tsunami travels towards the shore, both the water depth h and the tsunami speed c decrease. The energy flux of the tsunami, which is dependent on both the wave speed and wave-height, remains nearly constant. Consequently, as tsunami speed diminishes, its wave-height grows (the so called shoaling effect). Thus a tsunami, which is imperceptible at deeper sea, may grow to be several meters in height near the coast. In the studies of waves, a distinction is made between the wave speed and fluid particle velocities [13]. Theoretically, the particles move in a circular motion at the water surface for deep-water conditions (h/L>0.5). However, as the wave length increases and a wave enters shallow-water conditions (h/L<0.05), the particle movement becomes elliptical. In shallow water the vertical motion of the water particle is negligibly small. In the case of tsunami in deeper ocean, the wave amplitude is small compared to the ocean depth, and the wavelengths are so long compared to the local water depth that linear long wave theory can be used to describe tsunami propagation. Under this assumption, the fluid particles under a tsunami move only horizontally, and the tsunami speed c can be calculated by [2]:

$$c = \sqrt{gh} \qquad (1)$$

In this equation g is the gravity acceleration and h is the water depth. The fact that the wave speed is only a function of h, explains why the wave amplitude increases as it reaches the shore. As the local water depth is reduced, the wave speed and kinetic wave energy decreases. The energy is transformed into potential wave energy and hence the wave height increases.

In addition to the wave speed there is also a "microscopic" point of view, which is the fluid particle velocity. Linear long wave theory assumes only a horizontal motion of the particles, in which the fluid particle velocity vector u=[u, v, w] is reduced in 2D motion to

$u(x,y,z) = u(x)$, $v(x,y,z) = 0$ and $w(x,y,z,) = 0$

The following formula [4] is used to calculate the tsunami horizontal particle velocity, u_{max}, according to linear wave theory:

$$u_{max} = \frac{a\sqrt{gh}}{h} = \frac{a\sqrt{g}}{\sqrt{h}} = a\sqrt{\frac{g}{h}} \qquad (2)$$

where the variables a, h and g represent respectively the wave amplitude, water depth and gravity acceleration.

2.2 Wave transformation over underwater barrier

An underwater barrier will affect the propagation and the properties of the wave. A wave passing over a high obstacle will be broken; therefore, linear wave theory is not valid anymore.

Wave breaking is a complex phenomenon and is extremely difficult to describe analytically. As shown in Fig 2, when the wave amplitude is large relative to the water depth, the wave speed increases and this results in breaking wave.

When the fluid particles collide with a barrier, the incoming wave energy is reduced due to wave reflection from the seaward face of the barrier and due to the flow separation at the barrier corners, leading to the generation of vortices. However, the largest energy losses are caused by prematurely wave breaking, forced in the shallower water over the barrier. The fluid particle velocity will be sufficient to give a

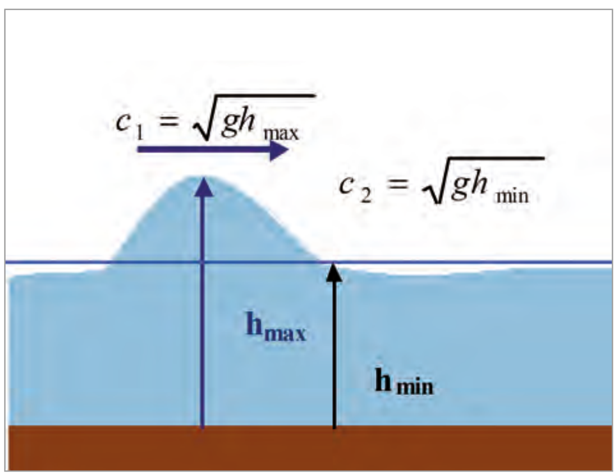


Figure 2: Breaking waves occur when the wave speed of one part of the wave is greater than the rest, which is the case when the amplitude is large.
$c_1 > c_2$

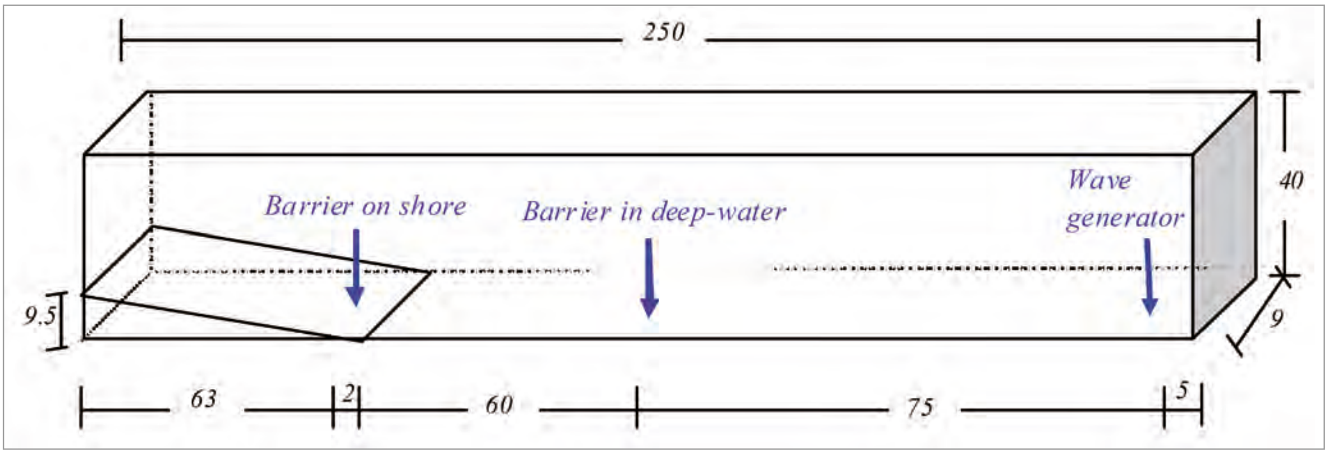


Figure 3: The tank used for the experiment (units in cm). The figure also shows the location of the barriers and the wave generator.

Reynolds number corresponding to a turbulent flow. Turbulent flow will produce a thinner boundary layer and smaller wake area than a laminar flow, which can be obtained by a very low fluid particle velocity [13].

3 Experimental Setup and Instrumentation

A tank measuring 9.0 cm × 40.0 cm × 204.0 cm was made out of plexiglas for this experiment. Inside the tank a shore was constructed with a height of 9.5 cm and length of 65.0 cm (Fig 3).

The tank was filled with 4 cm of water, which represents a depth of about 10 m in reality (model scale 1:250). Since depth of the water is an important parameter, the exact depth was carefully measured before each test. Solitary tsunami-like waves with a wave-amplitude of 2 cm were generated in the experiment.

For generation of tsunami waves, an electric pump was attached to the end of the tank. A spring was used to pull a piston upwards so that it was exactly under the water surface, and then it was released (Fig 4). This generated the same wave each time, while generation of surface waves were avoided.

In addition, a small rectangular piece with a size of 2.0 cm × 1.7 cm × 7.1 cm was cut out of Styrofoam to represent the underwater barrier. The experiment was performed with and without the barrier placed on the shore and also in the deep-water part of the tank. As mentioned above, the water in the tank represents about 10 m of water in reality. The Styrofoam piece corresponds to a barrier of

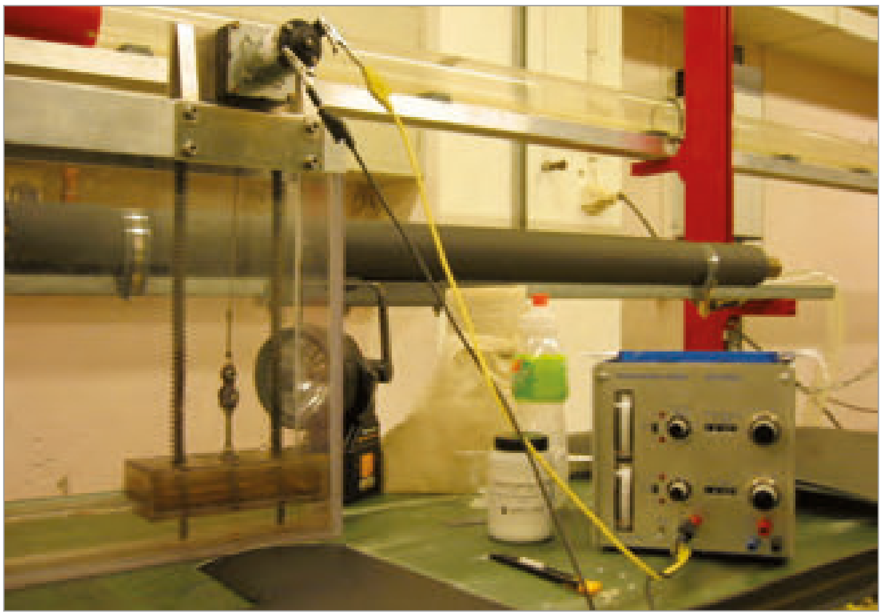


Figure 4: The electric wave generating pump.

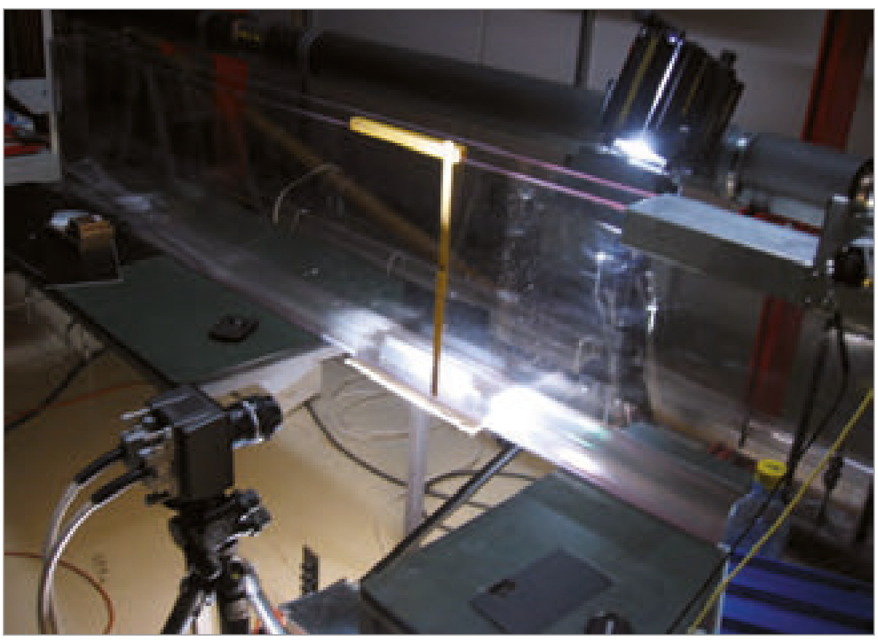


Figure 5: Lighting up of a section of the tank and recording by using a special digital camera.

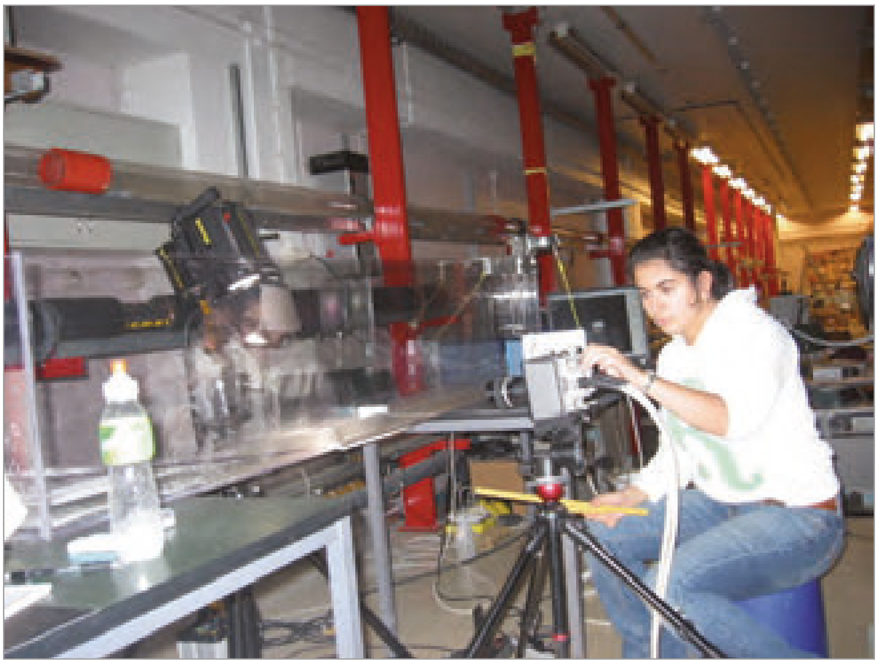


Figure 6a: The complete experimental setup

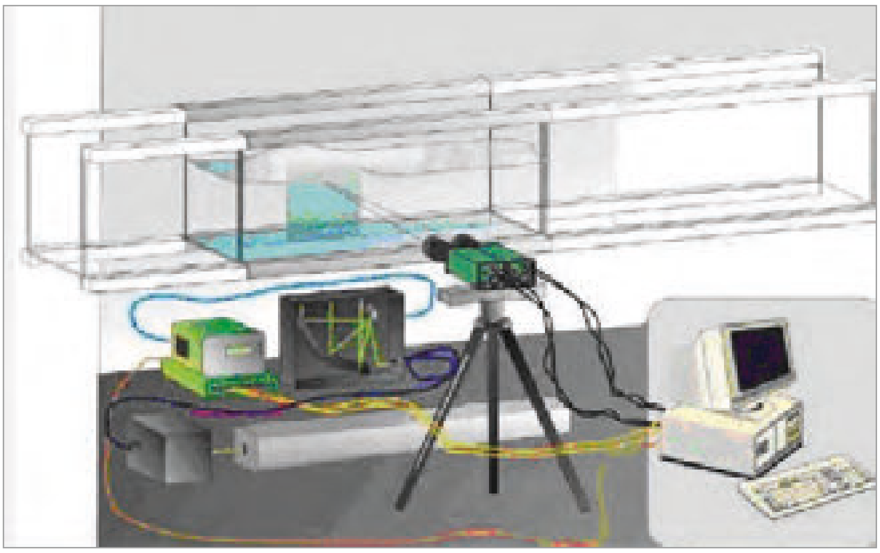


Figure 6b: Quelle: http://wacs.math.uio.no/flash/ungdom_sup.html

height 5 m, which is realistic to build and still allows normal sea traffic above it.

Small seed particles, called Polymid Seeding Particles, were added to the water to visualize the fluid particle motion. A strong spotlight was used to lighten up only a slice of approximately 2 cm × 20 cm of the tank (Fig 5). A special high resolution digital camera was utilized to capture the motions of the shallow water waves.

The wave speed and the horizontal particle velocity were measured in the deeper- and shallow-water parts of the tank. Two cases were considered: in the first test no barrier used, while in the second test a barrier was placed in front of the shore and on the beach (see Fig 3).

The movies recorded were then edited using the image-processing program Photron Fastcam viewer. Selected picture shots were then used in the computer program MathPiv to calculate the fluid particle velocity. The program was used to compare different frames and by recognizing the same tile in the frames it produces a velocity vector [14]. Additional processing was done on the data, such as converting from pixels to cm, to be able to calculate the speed of the tsunami (Fig 6).

In order to be able to compare the different experimental results, the following factors that may affect the behavior and properties of the wave must be kept constant:

- Homogeneity: one must use one medium to avoid internal waves produced in the interface between the two media.
- Air pressure: the air pressure also has some significance on how easily the wave propagates.
- Temperature: increase in temperature can increase evaporation and also expand the fluid.
- Viscosity: surface waves are dependent on surface tension and hence viscosity.

4 Analysis of Data

Necessary information was gathered to calculate the parameters of the tsunami wave at the deep and shallow water parts of the tank for both cases with and without the barrier.
In order to calculate the theoretical wave speed from Eq. 1, the initial depth of the water was measured, and the uncertainty of the wave speed was computed from:

$$\Delta c_{theory} = c\left(\frac{1}{2}\times\frac{\Delta h}{h}\right) \quad (3)$$

The theoretical fluid particle velocity (Eq. 2) was computed by using the measured water depth, h, and the amplitude, a, of the generated wave. The uncertainty of the particle velocity is:

$$\Delta u_{theory} = u\left(\frac{\Delta a}{a}+\frac{1}{2}\times\frac{\Delta h}{h}\right) \quad (4)$$

The wave speed in the experiments was calculated from the video-shots. By reading the distance moved by the wave crest during a certain time interval, the speed was found, and the corresponding uncertainty was computed according to:

$$\Delta c_{experiment} = c\times\left(\frac{\Delta d}{d}+\frac{\Delta t}{t}\right) \quad (5)$$

For the determination of the experimental values of the fluid particle velocity, the program MathPiv was used; the particle velocity (u) at different water depths (h) within the water column, at distances (x) in the range 72-78 cm (deep water) and

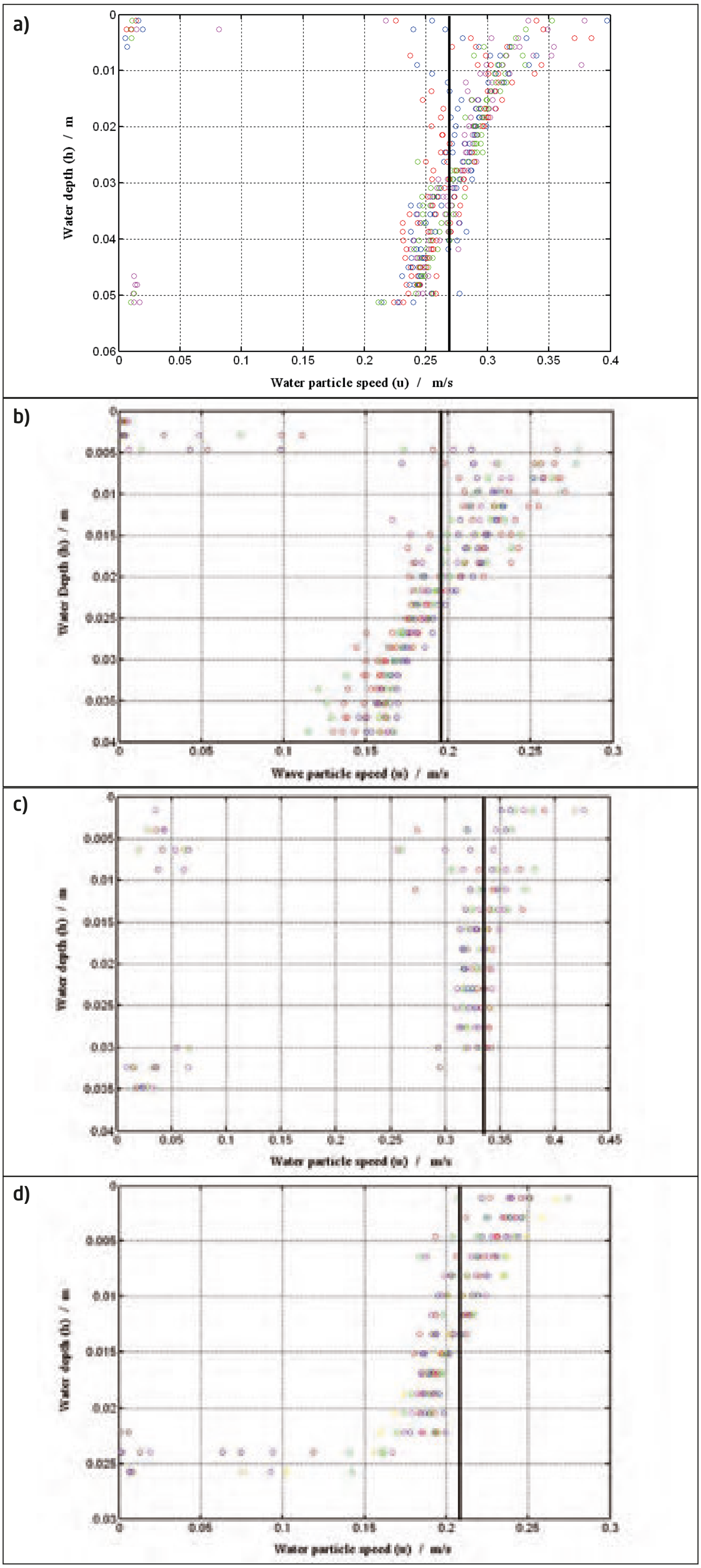


Figure 7: The horizontal particle velocities at different locations along the tank. The particles velocity in the different water columns are marked with circles, and the solid line shown the average horizontal particle velocity:
a) Deep-water part, without barrier (at 72-78 cm from wave generator);
b) Deep-water part, with barrier (at 72-78 cm from wave generator);
c) Shallow-water part, without barrier (at 134-140 cm from wave generator);
d) Shallow-water part, with barrier (at 134-140 cm from wave generator)

134-140 cm (shallow water) from the wave generator were computed. At different horizontal coordinates, x, the water depth was plotted against the fluid particle velocity, u, using the software MatLab (Fig 7). This provides the water particle velocity field, for different locations along the tank, at different water levels within the water column. The water particles on top of the wave or at the bottom of the seabed cannot move freely, thus these points were neglected in computing the average wave particle velocity. For the case with the barrier, the plotted data was taken from the point where the particles were no longer disturbed. Standard deviation of the particle velocity values was found by using all the raw data by the formula:

$$S_n = \sqrt{\frac{\Sigma(u_1 - u_2)^2}{n}} \qquad (6)$$

5 Discussion of the Results

This section summarizes the results of the experimental study as listed in Tables 1 and 2. As mentioned earlier and indicated by equations 1 and 2, the wave speed should decrease as the wave moves towards the shallower water depth, while the fluid particle velocity should increase.

5.1 The case without barrier

The experimental values for the wave speed and the fluid particle velocity are in good agreement with the values calculated from the theoretical formula (see Tables 1 and 2). It can be seen that the wave speed decreases from 0.619 m/s to 0.548 m/s as the wave moves towards the shore. The particle velocity, on the other hand increases from 0.270 m/s in the deep water to 0.328 m/s near the shore, which corresponds to an increase of 22%.

5.2 The case with barrier

When the barrier was placed in the tank, the wave speed was dramatically affected.

	Deep part		Shore	
	Without Barrier	*Behind Barrier*	*Without Barrier*	*Behind Barrier*
Theoretical	0.618 ± 0.016	0.610 ± 0.016	0.505 ± 0.019	0.524 ± 0.019
Experimental	0.619 ± 0.044	1.090 ± 0.095	0.618 ± 0.016	0.548 ± 0.103

Table 1: Wave speed c [m/s]

	Deep part		Shore	
	Without Barrier	*Behind Barrier*	*Without Barrier*	*Behind Barrier*
Theoretical	0.332 ± 0.040	0.239 ± 0.038	0.425 ± 0.074	0.392 ± 0.045
Experimental	0.270 ± 0.058*	1.092 ± 0.023*	0.328 ± 0.031*	0.207 ± 0.028*
	* Standard Deviation			

Table 2: Horizontal fluid particle velocity u [m/s]

In the deep-water part, the wave speed was calculated to be 0.610 m/s. However, when the barrier was placed there, the wave speed increased by 79 % to 1.090 m/s. The reason for this speed magnification is that when the wave moves above the barrier, it will break beyond that point. The properties of the breaking waves are different because they are no longer linear waves, and thus the formulas are no longer valid. This was again the case when the barrier was placed on the shore; the calculated wave speed was 0.524 m/s, but because of breaking of the wave the speed increased to 0.641 m/s. However, it is interesting to note that the increase in the wave speed was less when the barrier was at the shore, i. e. 18 % against 79 %.

The presence of the barrier also affects the fluid particle velocity, but contrary to the wave speed, the particle velocity decreases. In the case of the barrier placed in the deep-water part, the particle velocity that under ordinary conditions would be 0.239 m/s (theoretical value), was reduced to 0.192 m/s (experimental), i. e. a reduction by 20 %. At the shore, the reduction of the velocities is even greater. Without the barrier the particle velocity was expected to be 0.392 m/s, but with the presence of the barrier the speed was measured equal to 0.207 m/s, corresponding to a decrease by 47 %. Fairly similar conclusions were drawn for extremely nonlinear waves simulated numerically by Lynett [8].

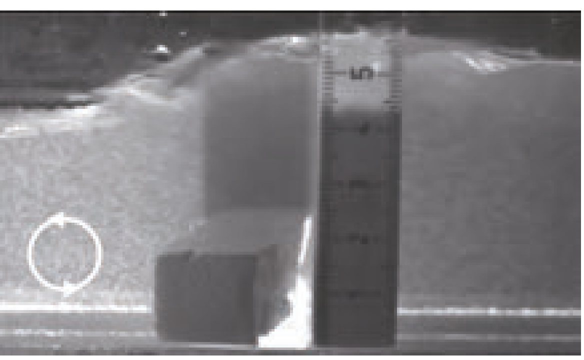


Figure 8: The vortex generation behind the barrier

The explanation for the velocity reduction when there is a barrier is that the particles lose a lot of energy. Some of the energy loss is due to the particles collision with the barrier, while a lot of energy is lost in the wake and turbulence that is created by the barrier. The vortex generated right behind the barrier, consumes a lot of energy (Fig 8). Thus the particles speed after this turbulence and vortex is lower than when there is no barrier.

6 Practical Considerations

Through this experiment the wave properties such as the wave speed and wave horizontal particle velocity were studied. The results from this experiment were used to verify the theoretical formulas for the wave speed and the fluid particle velocity. The theoretical formulas are only valid for linear waves and do not take into account the nonlinear effects associated with wave shoaling and breaking over the barrier. The experiment provided also the opportunity for measuring the speed and particle velocity of a breaking wave. An important observation is that as the wave moves from deep to shallow water, its speed decreases while the particle velocity increases.

It is the wave particle velocity that governs the destruction power of a wave. Therefore, in order to attenuate the incident tsunami energy, the wave particle velocity must be reduced. Based on the obtained experimental results, which showed that an underwater barrier can considerably reduce the fluid particle velocity, it can be concluded that building a barrier close to the shore is a potentially effective solution for reducing the damage by a wave. The observed reduction of about 50 % of the fluid particle velocity in this experiment corresponds to a reduction of 75 % of the kinetic energy.

Another advantage of building a barrier is that under certain incident wave conditions and structure geometry, it can force the incoming wave to break and therefore reduces the wave amplitude and its energy (Fig 9). The practical implication is that a construction of such a barrier can

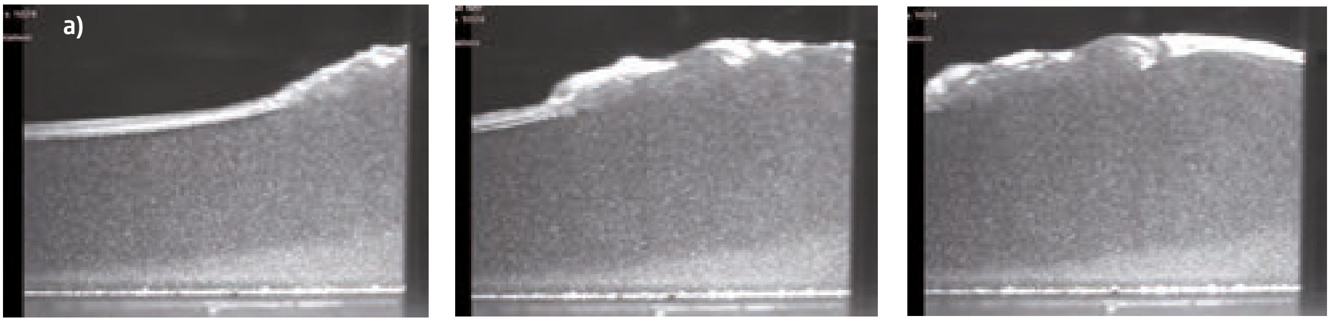
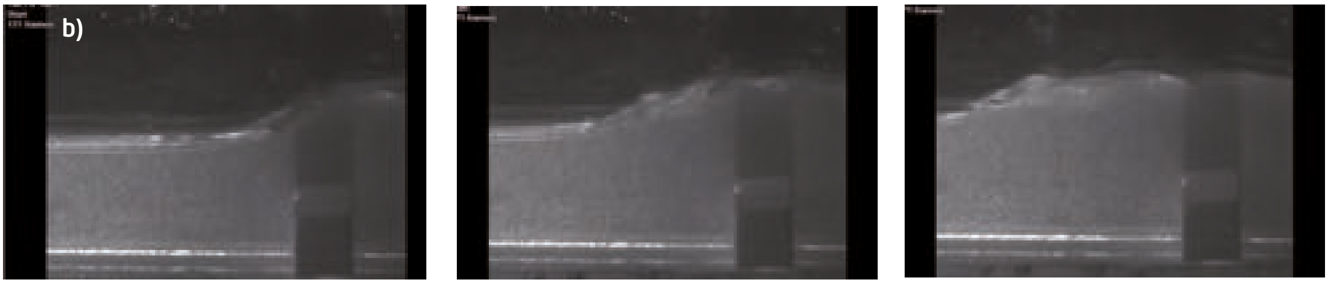


Figure 9: Several images from the experiment showing the sequence of wave propagation. a) At the deep part without barrier; b) Wave breaking due to the presence of the barrier.



reduce tsunami impact in the coastal areas prone to the tsunami hazard.
Geological studies in the aftermath of the catastrophe in 2004 have shown that the areas where the coral reef was more substantial the destructiveness of the tsunami wave was less [12]. This is another indication that the conclusions of this experiment are realistic.

The shape of the barrier should be a topic of further research. The ideal shape should ensure the structure stability under wave impact and cause significant wave energy loss. One should also consider where these walls should be built with regards to refraction and diffraction, so that the most vulnerable places are safeguarded.

In countries with limited resources simpler solutions could include coral reef growth or pile heaping of stones. This may still be sufficient to reduce the destruction force of a tsunami wave. To make the construction of the barrier more economically justifiable, one can install power turbines to generate power from daily waves and tides.

Acknowledgments

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