Chapter 8

Discussion About Tsunami Interaction with Fringing Coral Reef

Jean Roger, Bernard Dudon, Yann Krien, and Narcisse Zahibo

Abstract The recent catastrophic tsunamis show that it is now more than ever necessary to assess tsunami hazard for all coastal communities. In fact, facing the dangerous increase of population in low-lying coastal areas during the last decades directly linked to the reduction of the natural defences against sea assaults, including tsunamis, and considering the economy of most of the concerned countries, solutions should be found quickly to protect those populations and/or mitigate the hazard. In that way, recent studies and post-event field observations have highlighted the protective role played by coral reefs and the consequences of their destructions on the tsunami amplitudes. In this study previous results about the effect of fringing coral reef geometry on the tsunami amplitude are discussed using numerical modeling of nonlinear shallow water equations (NAMI-DANCE code). For this purpose, a set of different artificial Digital Elevation Models has been prepared in agreement with real bathymetric profiles and results of simulations are compared and discussed together with the conclusions obtained by the other authors.

Keywords Tsunami • Coral fringing reef • Numerical modeling

8.1 Introduction

After the 2004 Indian Ocean event causing a record death toll of about 300,000, several tsunamis have highlighted again the waves' capability of destruction, leading also to significant loss of life especially in the American Samoa, 2009 (Okal et al. 2010), in Chile, 2010 (Fritz et al. 2011), in Japan, 2011 (Stimpson 2011), and above all in Indonesia that has been the target of several other tsunamis

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since the big one (McAdoo et al. 2006; Fritz et al. 2007; Lay et al. 2011). Globally coastal communities attempt to find some solutions to face potential tsunami impacts (Rahman 2012) using different methods. According to recent works it is now clear that population protection depends mainly on education and awareness about the phenomenon and what to do in priority (Alexandra et al. 2009; Orcutt et al. 2011). Nevertheless it is also important to protect infrastructures besides human beings (Fraser et al. 2012).

Numerous research projects appeared in the early times after the 26th December 2004 tsunami, national as well as international, aiming at resolving major questions like which parts of the world coastlines are under tsunami threat, what is the potential of tsunami hazard, and how to protect the concerned coastal communities?

As in some places in Japan, the easiest way would be to build concrete sea defences (seawalls, tetrapod blocks, etc.) along the coasts but even in the case it could be feasible economically (Prasetya et al. 2008), the consequences on both environment and tourism especially in places annually frequented by hundreds of thousand people for their postcard sandy beaches could be irreversible (Schleupner 2005; Phillips and Jones 2006). In this way, Vuren et al. (2004) ask how coastal defences and societal activities in the coastal zone are compatible. In addition to this, Airoldi et al. (2005) try to propose an ecological perspective for the deployment of coastal defence structures but they would certainly be reserved for economically-rich countries, most of time less concerned by tsunami impacts. So to avoid this, people look at available natural means which could be rehabilitate and/or preserved in order to protect human beings against potential destructive tsunami waves (Tanaka 2009).

Studies dealing with the impact of several tsunamis after 2004 shows clearly that mangroves, coastal forests (like she-oak forests for example) and coral reefs represent natural barriers (Chatenoux and Peduzzi 2007; Kerr and Baird 2007; Cochard et al. 2008; Yanagisawa et al. 2009). The present problem is that the forests and mangroves tend to disappear globally, due to the dramatic increasing of coastal population (<100 km from shoreline) during the twentieth Century imposing a conversion of these flat and fertile coastal landscapes into agricultural and more generally industrial purposes (Valiela et al. 2001, 2009; Valiela 2006). Coral reefs seem to be less impacted even if they also tend to disappear for reasons like anthropogenic impacts as pollution and overfishing, but also because of storms and global warming (Wilkinson 1999; Bouchon et al. 2008a, b; Sale 2011). The main interest of coral reefs and finally, the reason of this study, is that it is generally accepted that they represent an efficient mean of protection against wave assaults (wind waves, swells, tsunamis) by most of coastal communities (Clark 1991; Frihy et al. 2004; SDMRI Report 2005; Liu and Ghidaoui 2009), being able to reduce classic wave energy until 71 % between the forereef and the reef crest (Lugo-Fernandez et al. 1998). But are they as efficient for tsunami waves as for wind-driven waves? What is the reality according to recent tsunami observations? What are the limitations of this free protection?

Nott (1997) shows that the tsunami triggered by the 1994 East Java Mw = 7.6 earthquake has been able to penetrate through the Australian eastern fringing coral reef off Cairns due to substantial gaps (funneling effect in 5–10 km wide passages) and impact the coast in front of these gaps as in the case of storm-generated waves (Young and Hardy 1993).

Several recent studies have been led to demonstrate the role played by coral reefs on tsunami waves, focusing on field observations and/or numerical modeling in order to assess which parameter of the geometry or the bottom friction would have the worst consequences on the tsunami amplitude and frequency content (Baba et al. 2008), flow speed (Fernando et al. 2008) and coastal run-up (Kunkel et al. 2006; Liu and Ghidaoui 2009; Gelfenbaum et al. 2011). In the following we discuss the impact of parameters as reef width, lagoon width, water depth, friction or the presence of gaps, using an artificial bathymetric model (a digital elevation model, D.E.M.) of a coral reef facing a sloping beach on which we model tsunami generation and propagation with NAMI-DANCE modeling code. This study follows principally the work of Kunkel et al. (2006) and Liu and Ghidaoui (2009).

Definition

Commonly, a fringing reef is a reef located close to the shore with a maximum separation of several hundred meters (i.e. the backreef channel or shallow lagoon width, also called ‘boat channel’) with a depth of maximum 5–10 m, to distinguish with a barrier reef, separated from the coast by a deep water-lagoon (Kennedy and Woodroffe 2002; Smithers et al. 2006). As indicated by Kennedy and Woodroffe (2002), the simplest fringing reef shows a reef crest directly attached to the shoreline, without backreef channel. Figure 8.1 shows an example of the typical scheme of a fringing coral reef located behind a barrier reef (Martinique, French Caribbean Island).

A depth profile of high resolution multibeam bathymetric data from the SHOM (Service Hydrographique et Océanographique de la Marine, France) reveals the typical coastal morphology of such coral environment. Geographic location of Martinique Island is indicated on the Google Earth view.

8.2 Tsunami Modeling

8.2.1 Modeling Code

NAMI-DANCE is a numerical modeling code used in this study. It is a modified version of the Japanese TUNAMI N2 numerical code (Imamura 1989, 1995) based on the solution of nonlinear shallow water equations (Zaytsev et al. 2009). The initial deformation calculation is based on elastic dislocation computed through Okada’s formula (1985). This method assumed an instantaneous displacement of the sea surface identical to the vertical deformation of the seafloor (transmitted

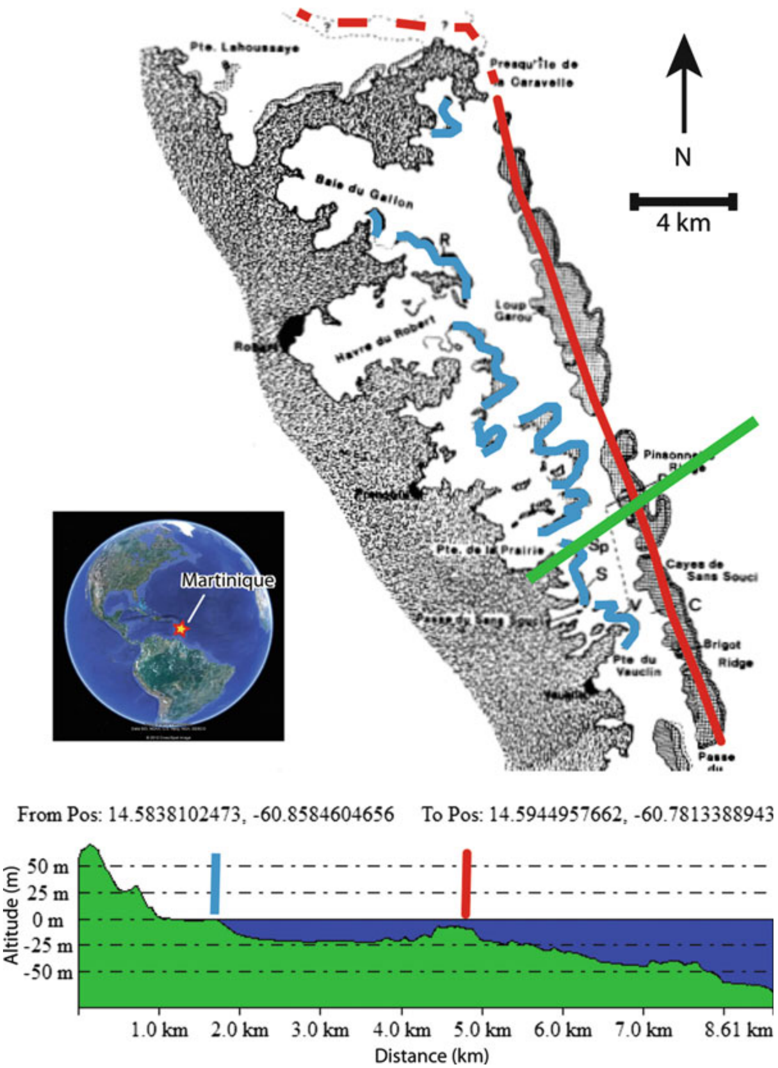

Fig. 8.1 Example of a combine coral reef along the eastern coast of Martinique Island: the *blue* and *red lines* highlight respectively the fringing and barrier reefs (Over a picture from Adey et al. 1977)

without losses to the entire water column), and solves the hydrodynamical equations 8.1, 8.2 and 8.3 of shallow water written in cartesian or spherical coordinates (Imamura et al. 2006). Non-linear terms are taken into account, and the resolution is carried out using a second-order explicit leap-frog finite different scheme. Wave dispersion is also considered.

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \tag{8.1}$$

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)+gD\frac{\partial \eta}{\partial x}+\frac{\tau_x}{\rho}=0 \tag{8.2}$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)+gD\frac{\partial n}{\partial y}+\frac{\tau_y}{p}=0 \tag{8.3}$$

$\mathbf{D} = \mathbf{h} + \boldsymbol{\eta}$ corresponds to the total water depth where h is the still water depth and η the sea surface elevation; v is the horizontal velocity vector; M and N are the water velocity fluxes in the x and y directions; τ_x and τ_y correspond to the bottom friction in x and y directions; g is the acceleration due to gravity (for more details see Dao and Tkalich 2007).

As most of tsunami modeling codes, this one allows the introduction of a specific initial disturbance like a single leading wave (solitary wave) as we will show in the following. It allows also the adjustment of the bottom friction coefficient f, linked to the Manning's roughness coefficient n by relation 8.4; the value of the Manning's roughness coefficient is set to 0.025 s/m$^{1/3}$ by default, a value commonly used, corresponding to a sandy bottom or bed rock cut channel (Linsley and Franzini 1979; Venturato et al. 2004), i.e. mildly rough interface. The value for coral reefs is not well-known as indicated by Kunkel et al. (2006). Imamura (2009) notices that this coefficient should be considered principally when the spatial grid size is larger than the scales of structures: in that case the bathymetric features are not correctly reproduced and thus the interaction between them and the waves is not well reproduced. In our case, the spatial resolution of the grid being 2 m, it encompasses largely the reef structure wavelength. Thus the role played by the friction coefficient will not be shown in the following as it has already been discussed by Kunkel et al. (2006): the authors conclude that the frictional effect lead to an energy dissipation of tsunami waves underlined by a run-up decrease of about 50 % for a variation of the drag coefficient of 0.03 to 0.1; the relation between Manning's and drag coefficients is explained in Rosman and Hench (2011). Fernando et al. (2008) reached the same conclusion of a considerable impact of coral friction on wave propagation and tsunami flow speed using a flume experiment with a synthetic coral reef showing a gap or not. Another part of energy dissipation is also due to wave breaking or reflection when passing through the reef, especially in the case of a reef located far offshore (typically a barrier reef).

$$n=\sqrt{\frac{fD^{\frac{1}{3}}}{2g}} \tag{8.4}$$

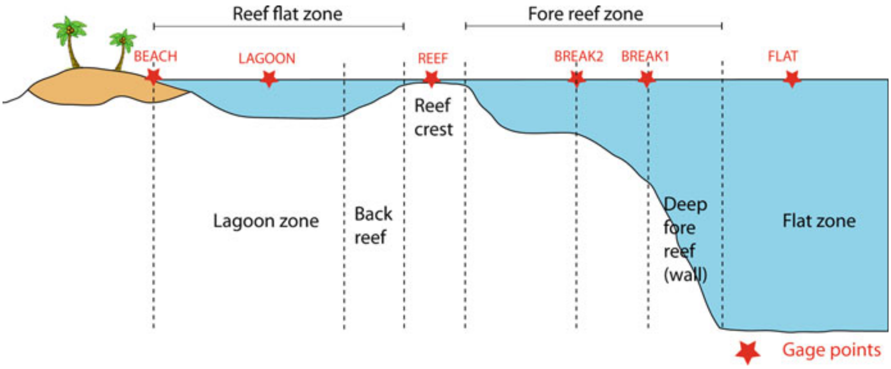

Fig. 8.2 Schematic profile of a coral reef in front of a sloping beach (Adapted from http://geology.uprm.edu/Morelock/reef.htm)

8.2.2 *Artificial DEM: Scenarios*

For the purpose of this study, because of the multiplicity of existing geometries of fringing reefs, a typical fringing reef profile presented in several previous studies concerning coral reefs (Fig. 8.2) has been chosen to build an artificial D.E.M. with adaptive geometry (Fig. 8.3).

Tsunami propagation is calculated over a 2 m – resolution bathymetric grid (i.e. D.E.M.) of dimension 1,500 × 1,500 m of a schematic coral reef in front of a sloping beach. Aiming to determine the role played by the main parameters as the reef width, the lagoon width, the channel width, the water depth upon the reef and the link between all of them, a set of different grids georeferenced in geographic coordinates has been prepared using a MATLAB subroutine. The resolution has been chosen with respect to real coastal feature (coral reef) wavelengths in order to reproduce as well as possible the shoaling effect, resonance phenomenon, etc.

The water thickness above the reef crest allows to test the case of a tsunami occurring at the same time of a storm surge or to consider the tide (low or high tide).

Here we only show the main results obtained with a handful of scenarios whose characteristics are presented in Table 8.1. An example of 3-dimensionnal D.E.M. is presented on Fig. 8.4: it corresponds to the case of a 100 m-wide reef with a 100 m-wide channel enclosing a 300 m-wide lagoon.

Tsunami propagation is calculated over each D.E.M. using the same initial deformation. For this preliminary study the initial deformation of the sea surface corresponds to a 3 m-high leading wave (only the positive peak) generated in the grid domain (Fig. 8.5) and showing a shape mimicking roughly a real tsunami wave. Six synthetic virtual tide gages (mareographs) have been located on this grid in order to record wave profiles as a function of time in strategic sites.

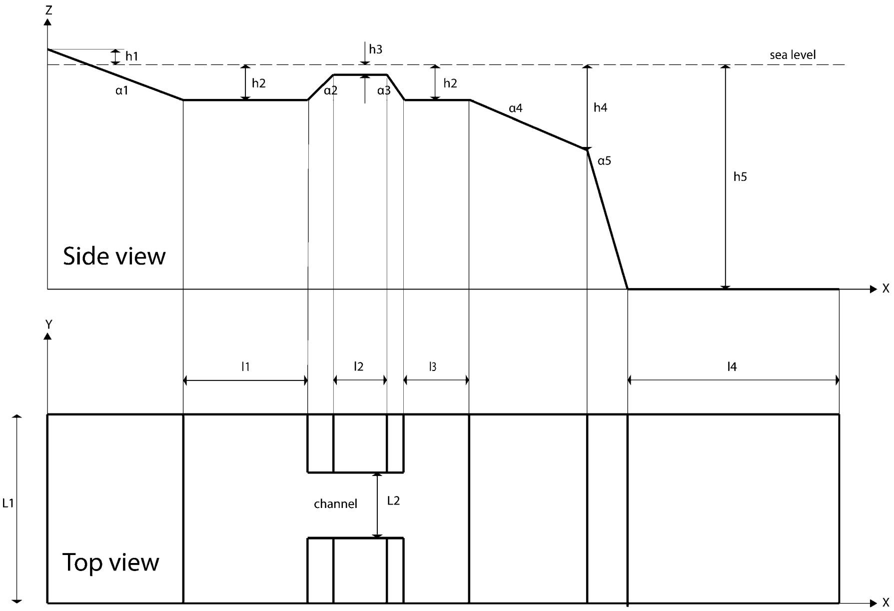

Fig. 8.3 Profile and top view of an idealized coral reef showing a gap in front of a sloping beach

Table 8.1 Interesting parameters of several tested cases: l_lagoon, h_reef, l_reef, l_channel correspond respectively to the lagoon width, the water thickness upon the reef crest, the reef width and the channel or gap width

model_number	l_lagoon (l1)	h_reef (h3)	l_reef (l2)	l_channel (L2)
1	50	0	10	10
2	50	0	10	50
3	50	0	10	100
4	50	0	50	10
7	50	0	100	10
10	50	1	10	10
12	50	1	10	100
19	100	0	10	10
37	300	0	10	10

8.2.3 *Results*

Propagation of a tsunami-like wave (the leading wave) has been done upon 60 different bathymetric grids. The interaction between this wave and the coral reef is shown on Fig. 8.6. It highlights the wave shoaling on the forereef because of depth decreasing, overtopping of the reef crest, refraction through the reef due to the presence of a gap and reflection on the shoreline. Run-up calculations are not shown here as they have already been discussed by Kunkel et al. (2006).

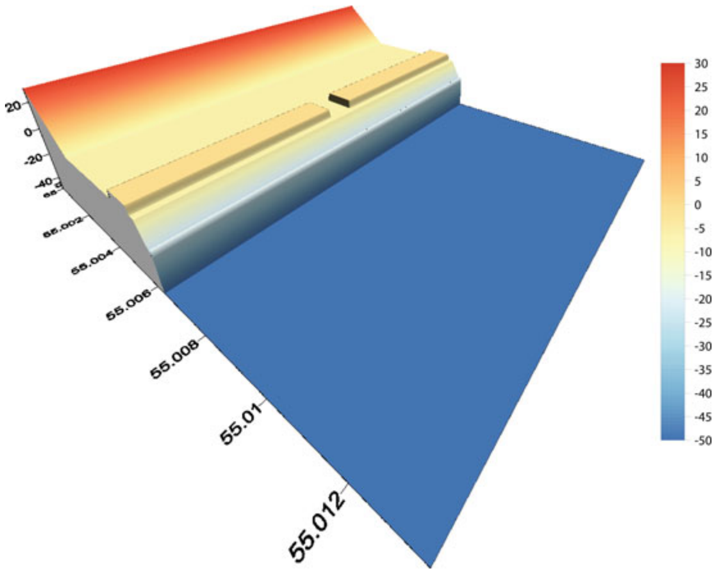

Fig. 8.4 Example of a D.E.M. prepared for tsunami propagation

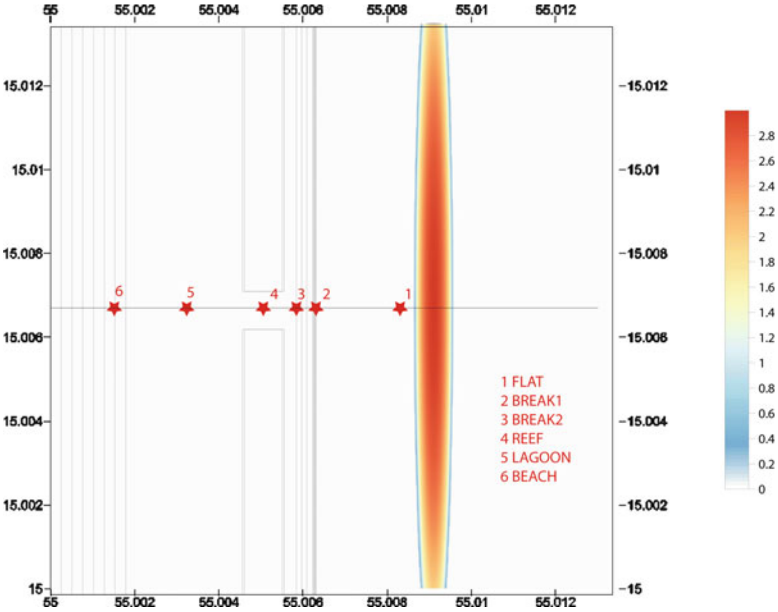

Fig. 8.5 Initial surface deformation (*top view*) obtained with NAMIDANCE in front of the reef (the *black rectangular lines* represent the bathymetric and topographic isohypses with a step of 5 m). The tides gages used to compare the signals are located with *red crosses*

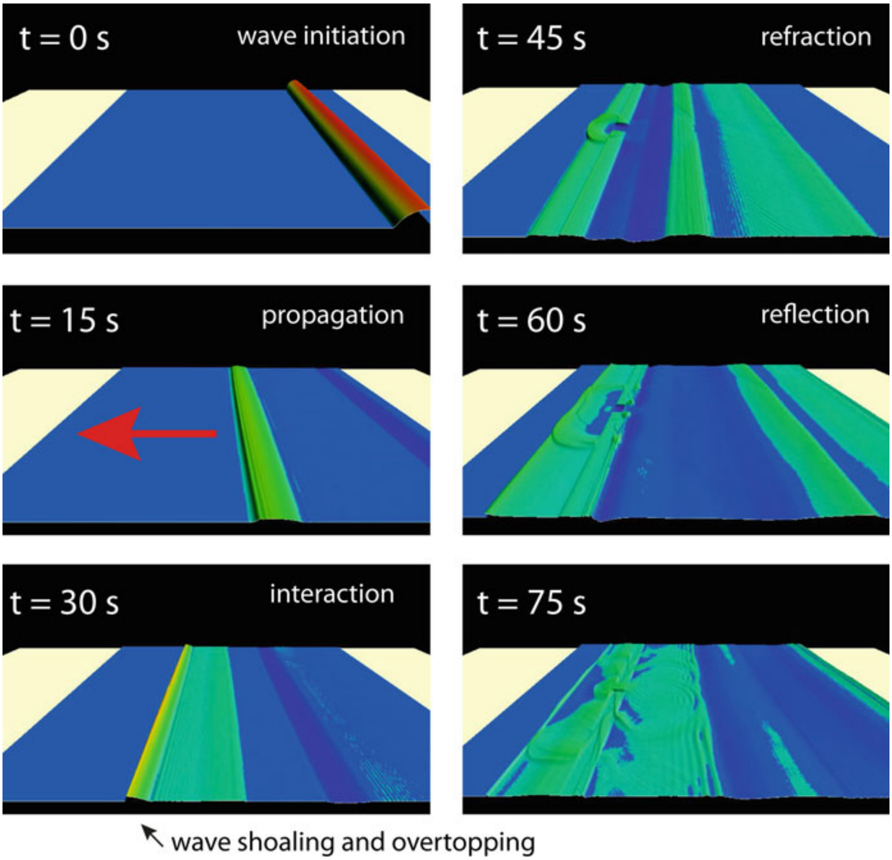

Fig. 8.6 Tsunami initiation and propagation (*red arrow* indicates direction) sketch towards a fringing coral reef showing interaction at a time step of 15 s

Figure 8.7 represents the maximum wave heights reach on each point of the grid after the propagation time. It reveals that the maximum wave heights reached in the near region behind the gap are more important than in region located behind healthy reef (without gap) as shown by Liu and Ghidaoui (2009). The gap (channel) in the reef leads to the diffraction of the incident wave-train which is followed by two main wave paths propagating in the lagoon towards the beach. They could be explained by wave interference between the refracted wave in the gap, the reflected wave on the beach and the overtopping wave. Amongst the 60 tests done during this study, we will concentrate on the most important related to post-event field observations:

(a) The sensitivity of the gap width is highlighted on Fig. 8.8a with 3 results of tsunami propagation at the same point (gage 5, Fig. 8.5) inside the lagoon for respectively 10, 50 and 100 m-wide channel. It indicates that an identical

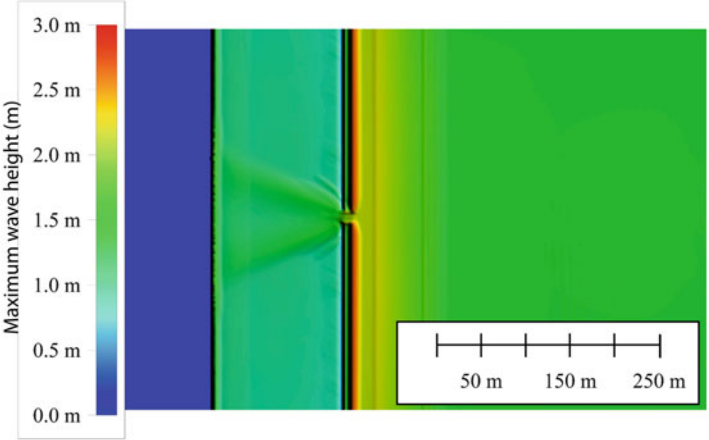

Fig. 8.7 Maximum wave height map of a scenario with a gap in the reef. It highlights two main wave paths inside the lagoon

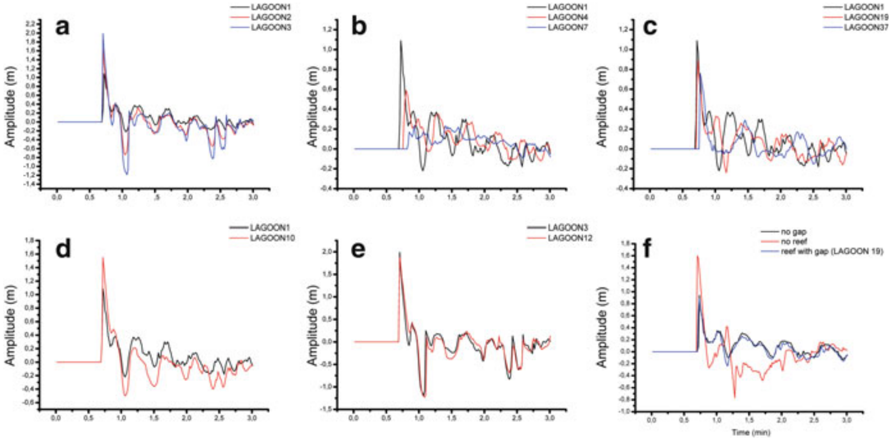

Fig. 8.8 Tide gage comparisons; the name of each gage LAGOON# refers to a number of gage in Table 8.1. In each case only one parameter changes: (**a**) reef channel width: 10, 50 and 100 m; (**b**) reef width: 10, 50 and 100 m; (**c**) lagoon width: 10, 50 and 100 m; (**d**) reef crest depth over a 10 m-wide reef: 0 and 1 m; (**e**) reef crest depth over a 100-m wide reef: 0 and 1 m; (**f**) no gap, no reef and a reef with a 10 m-wide gap

incident wave would have more energy, in terms of maximum wave amplitude, passing through the coral reef and thus able to reach the shore and inundate it

(b) Variation of the reef's width from 10 to 50 and 100 m (Fig. 8.8b) highlights that the wave amplitude near the shore will be less important with a larger reef. The incoming wave showing a wavelength of about 100 m is reduced by about 25 % and 85 % over a 10-m wide and 100-m wide reef respectively (Fig. 8.9). It is in

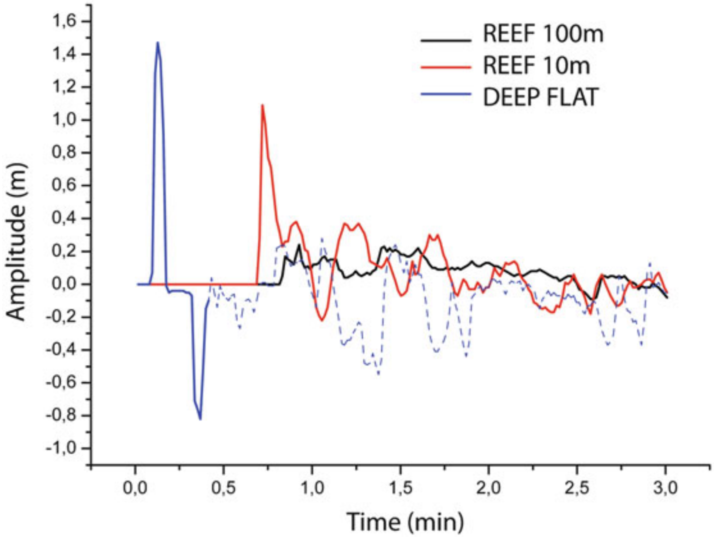

Fig. 8.9 Wave attenuation as a function of reef width: *blue curve* represents the initial signal recorded near the source; *red* and *black curves* represent respectively the recorded signal in the lagoon after passing over a over 10 m and 100 m-wide reefs

agreement with results of numerical modeling carried out by Mohandie and Teng (2009) who indicate that the reef is effective as a natural barrier for tsunamis with a width of about the same order of magnitude as the incoming wavelength

(c) In the same way, Fig. 8.8c shows that wave amplitude (of the first peak) will be less important with a larger lagoon

(d) and (e) The tests of the role played by the water depth upon the reef crest indicate that this water depth has not a so-significant impact on the wave amplitude as the precedent parameters if the reef is 100 m-wide, but upon a 10 m-wide reef, a water depth of 1 m leads to larger wave amplitude in the lagoon than with a water depth of 0 (Fig. 8.8d, e)

(f) Figure 8.8f illustrates the variation of signal with or without a gap in a 10 m-wide reef, and with and without a reef. As it has been already demonstrated, the presence of the reef has a direct impact on the amplitude of the tsunami near the coast. With unchanging roughness parameter the presence of a reef nearly divides by two the wave height in the lagoon

The tsunami height inside the lagoon after passing upon a reef without gap or with a 10 m-wide gap does not show substantial difference than in the case of a 50 or 100 m-wide gap (Fig. 8.8a) but however, the wave height without gap is less important, in agreement with Fernando et al. (2008) or Marris (2005).

8.3 Discussion and Conclusion

Our methodology of using an artificial D.E.M. that could be adapted for all the situations provides a useful tool to test the role played by each parameter of the geometry of a coral platform.

Our results agree with recent numerical experiments and several reported witnesses of a tsunami particular behavior linked to the existence of a fringing coral reef over the past two decades.

The role played by gaps is strongly underlined and converged on all the previous results. Indeed gaps allow a larger part of wave energy to pass through the reef contrarily to good-health reef (without gaps) in addition to the speed increase of the water flow due to a funneling effect inside the gaps (Liu and Ghidaoui 2009; Tanaka 2009). Besides, Nott (1997) indicates that the 1994 tsunami was probably amplified when passing through those gaps or as a result of resonance, diffraction or refraction phenomenon between the reef and the coast. He concludes that Cairns coast is finally not protected against such waves. Despite this, the role played by gaps and coral friction in general has been confirmed recently several researsch teams as Fernando et al. (2008) who discuss about the 2004 Sumatra tsunami impacting Sri Lanka coastlines. In their study they clearly demonstrate that the variation of friction underlined by the poaching and/or destruction of corals, equivalent to the creation of gaps within the reefs, leads to a substantial increase of tsunami flow velocity, because of reducing the bottom drag coefficient or roughness coefficient (Rosman and Hench 2011).

This is in agreement with the work of Lowe et al. (2005) who study the energy dissipation over a reef for classic waves; they conclude that the attenuation is due to the bottom friction often prevailing on wave breaking (on the contrary of what happens on a sandy beach). This is further demonstrated for tsunami waves by Kunkel et al. (2006) whose numerical experiment of tsunami propagation over a reef allow to propose a relation between run-up and drag coefficient (directly linked to the roughness coefficient; Wu et al.,1999).

The previous authors, which work has been partially tested with another method by Liu and Ghidaoui (2009), show also that the run-up over an idealized topography located behind the reef is directly linked to the reef width; but they are cautious with the results interpretation underlining the dependence of the run-up with the incident wavelength and amplitude as well as the geometry and health of the reef.

In the same way, Baba et al. (2008) model the propagation of the 2007 Solomon Islands tsunami through the Australian North-eastern coastline with and without the Great Barrier Reef and conclude that the reef reflects much of this low-amplitude tsunami energy, that the energy passing through is divided because of the gaps, and above all, that in addition to wave shoaling and breaking, the reef slows the waves down, delaying the tsunami impact.

They also indicate that the bottom friction of the reef should influence the tsunami as previously tested by Kunkel et al. (2006), hypothesis that has been confirmed more recently by the work of Gelfenbaum et al. (2011) for the 2009

American Samoa tsunami. On the contrary, the effectiveness of the reefs protective role is debated theoretically by Lynett (2007) who concludes that for very small obstacle lengths, i.e. typically a fringing coral reef compared with travelling tsunami wavelength, the reduction induced by the reef on the tsunami run-up and the maximum velocity will be inconsequential.

In that way, Roeber et al. (2010) demonstrate that the shallow reefs surrounding Tutuila Island were not enough to protect the coastline from the 2009 Samoa tsunami and they add the report of local resonances of short-period dispersive waves due to energy trapping within shallow lagoons, triggering more catastrophic consequences, highlighted on site by large disparities of impact along the coast. Nonetheless, the different conclusions reached by all these studies seem to agree globally with the fact that everything depends primarily on the reef width which induce dissipation through bottom friction, the presence and size of gaps, and on the incident wave height, especially if it exceeds the average depth of the top of the reef.

To summarize, in this study we show that the geometry and the location of the fringing coral reef (more or less close to the coast) including gaps or not plays an important role on the tsunami behavior in agreement with the existing studies (Kunkel et al. 2006; Fernando et al. 2008; Liu and Ghidaoui 2009; Baba et al. 2008; Gelfenbaum et al. 2011).

Tsunami waves seem to behave as classical waves as long as their characteristics stay within the same range of amplitude and respects the water depth over the reef. The tide or the weather condition (occurrence of a storm surge) should be considered accordingly to this fact. The greatest protection from destructive tsunamis will come from wide and high rough coral reefs, showing as little gaps as possible (Gelfenbaum et al. 2011).

Furthermore, the presence of gaps and the so-enclosed water body surrounded by the coral reef and the coast could induced indirect effects of tsunami arrival like flow speed increase or resonance phenomenon leading to a considerable rise of wave amplitude as shown by Roeber et al. (2010).

It follows from this work that rehabilitation and protection of coral reefs, leading to recover man-made gaps principally, should be considered as a natural mean of tsunami defence structure together with economically interesting purposes (touristic diving, fish nesting, etc.).

Prospects

A more accurate study should be realized using real bathymetric data to compare to well-known events including friction coefficient variations, tests of different incident waves and a numerical code using Boussinesq solution to reproduce as well as possible wave breaking and dispersion phenomenon (Roeber and Cheung 2012).

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