Geomorphology 253 (2016) 318–327

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Influence of reef geometry on wave attenuation on a Brazilian coral reef

Mirella B.S.F. Costa [a,c,*], Moacyr Araújo [b,c], Tereza C.M. Araújo [b,c], Eduardo Siegle [a,c]

[a] Instituto Oceanográfico, Universidade de São Paulo, Praça do Oceanográfico, 191, 05508-120, São Paulo, SP, Brazil
[b] Departamento de Oceanografia, Universidade Federal do Pernambuco, Av. Arquitetura, s/n, 50740-530, Recife, PE, Brazil
[c] INCT Ambientes Tropicais Marinhos, Brazil

ARTICLE INFO

Article history:
Received 18 December 2012
Received in revised form 28 October 2015
Accepted 1 November 2015
Available online 2 November 2015

Keywords:
Coastal erosion
Wave transmission
Coastal reef morphology

ABSTRACT

This study presents data from field experiments that focus on the influence of coral reef geometry on wave transformation in the Metropolitan Area of Recife (MAR) on the northeast coast of Brazil. First, a detailed bathymetric survey was conducted, revealing a submerged reef bank, measuring 18 km long by 1 km wide, parallel to the coastline with a quasi-horizontal top that varies from 0.5 m to 4 m in depth at low tide. Cluster similarity between 180 reef profiles indicates that in 75% of the area, the reef geometry has a configuration similar to a platform reef, whereas in 25% of the area it resembles a fringing reef. Measurements of wave pressure fluctuations were made at two stations (experiments E1 and E2) across the reef profile. The results indicate that wave height was tidally modulated at both experimental sites. Up to 67% (E1) and 99.9% (E2) of the incident wave height is attenuated by the reef top at low tide. This tidal modulation is most apparent at E2 due to reef geometry. At this location, the reef top is only approximately 0.5 m deep during mean low spring water, and almost all incident waves break on the outer reef edge. At E1, the reef top depth is 4 m, and waves with height ratios smaller than the critical breaking limit are free to pass onto the reef and are primarily attenuated by bottom friction. These results highlight the importance of reef geometry in controlling wave characteristics of the MAR beaches and demonstrate its effect on the morphology of the adjacent coast. Implications of differences in wave attenuation and the level of protection provided by the reefs to the adjacent shoreline are discussed.

1. Introduction

Coral reefs often exhibit a steep transition from relatively deep to shallow water (Wiens, 1962; Lowe et al., 2005). These reefs function as protective barriers (Lowe et al., 2005; Kench and Brander, 2006) where significant amounts of surface wave energy can be dissipated (Young, 1987; Wolanski, 1994), thereby sheltering the adjacent coastline (Gerritsen, 1981; Frihy et al., 2004). Although the morphological complexity of coral reef systems (broadly divided in 'fringing reef, 'barrier reef' and 'atoll') the dominant mechanisms of cross-reef wave dissipation have been identified as depth-induced wave breaking (Young, 1989; Gourlay, 1994; Massel and Gourlay, 2000) and bottom friction (Lowe et al., 2005). Moreover, coral reef organisms are known to form some of the roughest surfaces in the coastal ocean, so frictional dissipation rates may be an order of magnitude larger over reefs (Smith, 1993) than over a sandy bottom (Lowe et al., 2005). Thus, the wave energy is much smaller on beaches fronted by reefs (Frihy et al., 2004).

Estimates of wave height across coral reefs show an attenuation of 20–47% induced by bottom friction (Roberts et al., 1975; Gerritsen, 1981; Lugo-Fernández et al., 1994); as a wave propagates across the shallowest part of the reef, the attenuation by wave breaking can dissipate approximately 50–99.5% of the incident wave energy (Lugo-Fernández et al., 1998; Brander et al., 2004; Kench and Brander, 2006). The precise character of wave transformation and the spatial extent of energy dissipation is controlled by the morphology of the reef structure (elevation, reef slope, and reef flat width), the relative water depth at the reef edge (Gourlay, 1994; Hardy and Young, 1996; Nelson, 1996; Kench and Brander, 2006) and the characteristics of the incident waves (Kobayashi and Wurjanto, 1989; Gourlay, 1996a; Lowe et al., 2005).

Although coral reefs provide a well-known overall degree of protection, erosion has increased markedly in recent years on many tropical shores (Wilkinson, 2004), which has required the implementation of costly restoration programs and building of expensive coastal structures. Unlike siliciclastic beaches, which typically have moderate slopes and relatively smooth bottoms (Lowe et al., 2005), tropical beaches fronted by coral reefs generally have steep slopes, complex topography, and rough bottoms, which result in complex wave transformation processes that often make the role of reefs in shaping coastal morphology unclear.

During recent decades, the northeastern Brazilian coast has faced many erosion problems. One of the main features of this coast is the peculiar characteristic of coral reef growth parallel to the main shoreline axis (Laborel, 1965; Maida and Ferreira, 1997). Despite the presence of these reefs and their potential effect on coastal dynamics, little

* Corresponding author.
E-mail address: mirella_borba@yahoo.com.br (M.B.S.F. Costa).

http://dx.doi.org/10.1016/j.geomorph.2015.11.001
0169-555X/

attention has been given to their role in transforming the incoming waves and the implications this has on the regional coastal morphology. The aim of this study is to identify the geometric variability of the reefs on a stretch of the northeastern Brazilian coast and its effect on the transformation of waves as they propagate onto the adjacent shoreline.

2. Methods

2.1. Study area

Over a distance of 600 km (from 5 to 10° of latitude) along the Brazilian coast, coral reefs run parallel to the coast. The location and general morphology of the coral reefs are closely associated with the presence of beachrocks (Laborel, 1969; Dominguez et al., 1990). Although studies on the internal structures of the reefs have not been performed to date, it is thought that the coastal coral reefs are of Holocene age and have grown on top of submerged beachrocks (Laborel, 1969; Maida and Ferreira, 1997). In some areas, as many as three lines of reefs exist off the coast. Reefs that are exposed at low tide vary from 1 to 4 km in length, while submerged reefs can be as long as 10 km with tops that vary from 4 m to 8 m in depth (Dominguez et al., 1990). The depth of the water surrounding those reefs is seldom greater than 10 m.

Laborel (1969) made a detailed description of the area and named two main features: i. submerged reef banks, formed primarily by coral and coralline algae, and ii. "arrecifes", structures composed of beachrocks with only scattered corals and coralline algae on their outer side (in accordance with Ottmann (1960) and also later described by Guilcher (1983)). The reefs adjacent to the coast have, at present, part of their reef flats covered by siliciclastic sand and buried back-reef lagoons (Laborel, 1969; Leão and Kikuchi, 2011), which are defined as fringing reefs by some authors (e.g. Guilcher, 1983; Leão and Kikuchi, 2011). However, the whole reef system comprises several fully submerged reefs lines that are separated from one another longitudinally by sand flats and detached from the coast. The geomorphology and formation of these reefs are very similar to those of the reefs in Southeast Florida, which form a series of shore-parallel, progressively deeper, reef-like ridges. Lighty (1977) noted that it initiated as a fringing reef and transitioned to an extensive shelf-edge barrier reef as rising sea level submerged the back reef shelf margin. Due to their linear shapes, these have been referred as linear reefs (Moyer et al., 2003; Riegl et al., 2005; Banks et al., 2007; Walker et al., 2008; Walker, 2012). As in Brazil, the coral in Southeast Florida presumably settled and grew on the submerged cemented ancient shoreline deposits (Stauble and McNeil, 1985; Davis, 1997; Finkl, 2005; Banks et al., 2007) given this linear shape characteristic.

The reefs play a major role in coastal morphology (Laborel, 1969). As shown in Fig. 1, salients are present at the lee side of the semi-submerged portion of the reef line. Small embayments, which may contain mangrove swamps where creeks and rivers are present (Hartt, 1870; Branner, 1904; Dominguez et al., 1990), are formed in front of existing gaps in the reef.

Most coral reef formations along the Brazilian coast exhibit similar patterns of coral zonation. This consists of an algal-vermetid ridge at the intertidal reef crest; a *Palythoa* and *Millepora* zone immediately below the algal ridge; a *Mussismilia* spp. zone in the mid-section of the reef slope; and a *Montastraea cavernosa* zone on the lower reef slope. The coral fauna includes 18 species of scleractinian corals, with 15 hermatypic species and three ahermatypes. Seven of the 15 hermatypic species are endemic to Brazilian waters (Maida and Ferreira, 1997). The primary coral builders of the reefs are *Mussismilia harttii*, *Mussismilia hispida*, *M. cavernosa*, *Mileporas* and *Siderastrea* (Laborel, 1969).

The experiments for this study were conducted on the metropolitan area of Recife — MAR coast, Pernambuco state in northeastern Brazil (8°08′S, 34°53′W) (Fig. 1). MAR has the highest population density along the Brazilian coast and is intensely urbanized. Along its 18 km of coastline, approximately 40% of its backshore is fixed by hard engineering structures such as seawalls and groins. Tides in the region are low-mesotidal, with a mean spring tidal range of 2.07 m and mean neap tidal of 0.97 m. From September to February, southeast winds with average speeds of 2.6 m/s to 4 m/s prevail (FINEP/UFPE, 2009). Weaker east-northeast winds are more frequent during November and December. The offshore wave climate is mainly controlled by the trade winds, with east-southeast dominance, though during fall and winter, waves from the south are also present. They are generated by the passage of cold fronts (Pianca et al., 2010) and disturbances caused by extratropical cyclones over the South Atlantic Ocean (Innocentini et al., 2005). The highest waves occur during the winter months and come from the southeast, with maximum heights of 4.3 m and maximum periods of 17 s (Pianca et al., 2010).

2.2. Bathymetric survey

A detailed bathymetric survey of the reef zone was conducted using a single-beam 200-kHz echo sounder (Garmin 298 s with a GPS antenna for navigation and positioning) that sampled at a rate of three soundings per second. The sounder was mounted off the side of a monohull vessel (draft of 24 cm). A total of 180 reef profiles were measured covering the entire length of the study area, from the shoreline to the 20 m isobath. The profiles were perpendicular to the main shoreline axis and were spaced at approximate intervals of 100 m (Fig. 2). All depth values were tidally corrected to the vertical datum of the national nautical charts (Mean Spring Low Water — MSLW).

A similarity analysis of the 180 surveyed profiles has been conducted in order to group and define the reef morphology along the studied area. The profiles were grouped using a cluster similarity analysis between their depths from the first point (nearshore) to the last point (offshore). A Bray–Curtis similarity matrix was produced using rows of 25-m grid discretizations of each reef profile depth. The similarity matrix was then used to perform a hierarchical cluster analysis, using a group-average linking method to represent the reef geometry groups.

2.3. Wave and tide dataset

To evaluate the attenuation of a wave after its propagation across the reef, two S4s were deployed simultaneously, in front of (leeward) and behind (seaward) the reef at two different profiles — Profiles A and B. To represent the wave attenuation processes in areas with different reef geometries, the profiles and the exact position of the S4s (i.e., depth and distance from the reef edge) were defined according to the results of the reef geometry analysis. Thus, a total of four experiments were conducted, with two at Profile A (E1A and E1B) and two at Profile B (E2A and E2B). The campaign dates of each experiment are shown in Table 1.

Sea level displacements were measured at a sampling rate of 2 Hz by wave and tide recorders (InterOcean S4ADWi) operating in intermittent mode for 30 min every hour. The time-series of pressure fluctuations measured by the high-resolution sensor (4 mm depth resolution) were converted to the wave spectrum using a Fast Fourier Transform (FFT) algorithm. In the frequency domain, the pressure amplitude data were corrected for attenuation versus frequency and depth. Significant wave height was calculated as: $H_{m0} = 4\sqrt{m0}$, where m0 is the zeroth moment of the spectral density variance. For this work, we used the Hs from gravity wave frequencies between 0.333–0.0333 Hz (3–30 s). The water depth (MWD) was averaged every 10 min and tidal variations were derived from the difference of the water depth values and the MWD and adjusted to the vertical datum of the national nautical charts.