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Field observations and modeling of wave attenuation over colonized beachrocks

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ABSTRACT

Beachrocks are common coastal formations, constructed through the lithification of beach sediments by carbonate cements. The objectives of the present contribution were to (a) assess the impacts of beachrock benthic communities on nearshore wave dynamics; (b) present a numerical model, developed to simulate wave propagation over shallow nearshore waters characterized by both loose sediment beds and colonized/non-colonized beachrocks; and (c) discuss the structure and dynamics of beachrock macro-benthic communities in an E. Mediterranean micro-tidal beach (Vatera, Lesbos Island, NE Aegean Sea), as well as their interactions with the wave forcing. Field measurements of wave height and flow velocity were processed to assess shoaling wave energy dissipation due to bottom friction from the colonized beachrock outcrops. The equivalent Nikuradse hydraulic roughness of the beachrock surface, estimated through spectral wave attenuation calculations, was found to be around $k_N=0.13$ m. The corresponding wave friction factors were incorporated into a wave propagation model to obtain estimates of the wave-induced bed shear stress τ_w acting on the beachrock benthic communities. Information about the structure and characteristics of the latter was obtained through the collection and analysis of samples from 15 stations along a beach transect, during two months of the year (April and September) and the results showed that benthic communities at the beachrock habitat were very similar to the ones typically found at NE Mediterranean hard substrates. Wave-induced bed shear stress τ_w values were able to explain cross-shore variations in population density and biomass, both decreasing significantly above water depths of about $h=1.8$–2 m. The latter values corresponded, for the studied conditions, to shear stresses of about $\tau_w=2.2$ Nt/m^2. The present findings clearly show that nearshore wave patterns not only control to a certain extent the spatial structure of the beachrock habitats, but can be also influenced by them. Thus, hydrodynamics and beachrocks habitats constitute a complex system which remains very little understood and demands for further investigation.

1. Introduction

Beachrocks are coastal formations resulting from the cementation of beach sediments mainly by calcitic or aragonitic cements (e.g. Neumeier, 1999). Sediment cementation takes place either on the surface or, more commonly, beneath the littoral/intertidal sediments, and the resulting formations can be kilometers long and attain widths of hundreds of meters and thicknesses of up to several meters (e.g. Vieira and De Ros, 2006). Beachrock cementation has been attributed to different mechanisms, including the following:

(i) direct precipitation of $CaCO_3$ from the seawater due to increased water temperatures (Ginsburg, 1953);
(ii) mixing of sea- and fresh-water in the coastal aquifers, promoting changes in the $CaCO_3$ solubility (e.g. Milliman, 1974);
(iii) evaporation of percolating groundwater in arid regions with large temperature variability (e.g. Russell and McIntire, 1965);
(iv) CO_2 degassing from water tables with high dissolved $CaCO_3$ content (Hanor, 1978); and
(v) biological activity (e.g. Neumeier, 1999).

Most of the previous beachrock studies have focussed on cements (e.g. Arrieta et al., 2011; Erginal et al., 2012; Vincent, 2011), formation mechanisms (for a review, see Vousdoukas et al. (2007)) and their utility as proxies for past sea levels (Cundy et al., 2010; Desruelles et al., 2009). There have also been studies indicating that beachrocks may significantly affect beach morphodynamics, by altering sediment transport processes and inducing erosion of beach sediment that could result in outcropping of initially buried formations (Cooper, 1991; Vousdoukas et al., 2005, 2009a); with further implications on

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the recreational use of the beach (Vousdoukas et al., 2009b). However, despite the fact that beachrock formation and outcropping has been shown to be a common phenomenon of the global tropical and temperate coastline (Vousdoukas et al., 2007), there has been limited research on the impacts of beachrock outcropping on the ecological character of beaches (Brattström, 1992). Even fewer, if any, are studies concerning the impacts that beachrock benthic communities might have on the nearshore wave propagation.

In recent years there has been an increasing interest on the role of phytobenthos on shoaling wave attenuation (e.g. Guillén et al. 2008; Möller et al., 2011; Pratolongo et al., 2010). Nevertheless, there are still significant gaps in our understanding of these processes (for a review, see Vousdoukas et al. (2011a)), in comparison to those relating to flow attenuation in unidirectional flows that have been observed (Nepf and Vivoni, 2000; Tanino and Nepf, 2008) and modeled (Chen et al., 2011; Li and Xie, 2011; Li and Yu, 2010) in some detail. Similarly, there is very limited research on wave propagation over beachrock outcrops, colonized by benthic communities.

Therefore, the objectives of the present contribution were to (a) assess the impact that the presence of beachrock benthic communities might have on nearshore wave dynamics; (b) present a numerical model, developed to simulate wave propagation over shallow nearshore waters that combine the presence of both loose sediment beds and colonized and non-colonized beachrocks; and (c) discuss interactions between wave forcing and the structure and dynamics of beachrock macro-benthic communities in an E. Mediterranean micro-tidal beach (Vatera, Lesbos Island, NE Aegean Sea).

2. Study area

Vatera beach is a 7 km long, micro-tidal beach with spring tidal ranges less than 0.2 m (Tsimplis, 1994), located at the south coast of the island of Lesbos (NE Aegean Sea, Greece) (Fig. 1). The area is characterized by a Mediterranean climate with dry, hot summers (mean temperature 27 °C) and mild winters (mean temperature of 7 °C). The prevailing NE winds can routinely reach speeds of 20 ms^{-1}. However, as the embayment is open to the south, coastal hydrodynamics are mostly influenced by winds and waves from the southern sector, which are predominantly from the SE and SSE, and are associated with relatively small fetches and typically have speeds lower than 10 ms^{-1}. The SW winds, which have longer fetch reaching 100 nautical miles, are weaker and less frequent and do not contribute significantly to the local wave regime. Consequently, the wave climate at Vatera beach is mild, with significant wave heights (H_s) below 1 m during 98% of the time, annually-averaged wave period (T_p) of about 3.5 s, and mean winter and mean summer significant wave heights of about 0.4 m and less than 0.25 m, respectively. Nevertheless, significant wave heights during rare storm events can reach up to 3 m (Vousdoukas et al., 2009a).

Vatera is a 'pocket' beach that is confined by rocky promontories (Fig. 1a) and can be considered as a single coastal sediment cell, supplied by two seasonally flowing rivers found at its western and eastern margins, as well as by small ephemeral streams draining the low cliffs found along the central and eastern sections of the embayment (Fig. 1). Along the sub-aerial beach, sediments are generally poorly-sorted and coarse-grained, whereas the sediments of the submerged beach are finer (0.3 mm $< d_{50} <$ 0.5 mm), much better sorted and consisting mostly of clastic material. Beach-face slopes are steep along the western part of the beach (up to 16%), decreasing gradually towards the east.

Large tracts of the beach-face are occupied by beachrock outcrops of lengths varying from few meters to 200 m long, depending on the dynamics of the littoral sediment transport patterns that may result in occasional exposure, or burial of the formations (Vousdoukas et al., 2009a). Beachrock formations may extend up to 20 m inshore, buried under a sedimentary cover of up to 2 m thick, whereas the cross-shore lengths of the commonly exposed, sub-marine beachrocks can reach 15 m. Previous studies have shown that there is significant beachrock control on the beach profile and dynamics, with the outcrops forming effective barriers to cross-shore sediment exchanges between the sub-marine and sub-aerial beach, particularly with regard to the onshore transport (Vousdoukas et al., 2005, 2009a).

3. Methods

3.1. Hydrodynamic and topographic data acquisition

Field observations were undertaken in late April with the main objectives being to (i) assess energy dissipation between paired observation stations along a cross-shore beach profile with beachrocks (Transect A, Fig. 1) and estimate the associated wave friction factors and equivalent Nikuradse bed roughness values of the outcrops (Kamphuis, 1975); and (ii) use these estimates to calibrate a 1-D hydrodynamic numerical model used to quantify the cross-shore distribution of bed shear stress over beachrock outcrops colonised by benthic communities.

An Acoustic Doppler Velocimeter (ADV) containing a pressure sensor (PT1) mounted on an aluminum frame was positioned at St8 of Transect A (Figs. 1 and 2) to collect current velocity data at 0.06 m and pressure (wave) data at 0.35 m above the sea bed. Additional wave data were obtained by another pressure sensor (PT2), which was moved between different pre-defined stations (Fig. 2), always positioned at 0.35 m above the bed. All velocity and pressure data acquisition took place at 16 Hz, during synchronized 300 s bursts, followed by equal duration 'sleep-mode' intervals; two data bursts were obtained from each station. In this fashion, simultaneous water elevation burst measurements were acquired at 'paired' stations, which were then used in the wave attenuation analysis (see Section 3.2).

Levelling of the Transects A and B (Fig. 1a) for elevations (z) from −5 to +3 m relative to mean sea level (MSL) was obtained through standard topographic surveys, using a TopCom AT-G4 level. The upper beach was surveyed to a depth of 1.5 m with a spacing of 1 m, whereas the elevation of the sampling stations and the entire sub-marine profile, to a depth of about 5 m, was surveyed by a scuba diver. All levelling work took place under very calm wave conditions, and elevation data were subsequently reduced to a common datum using tidal gauge data records from

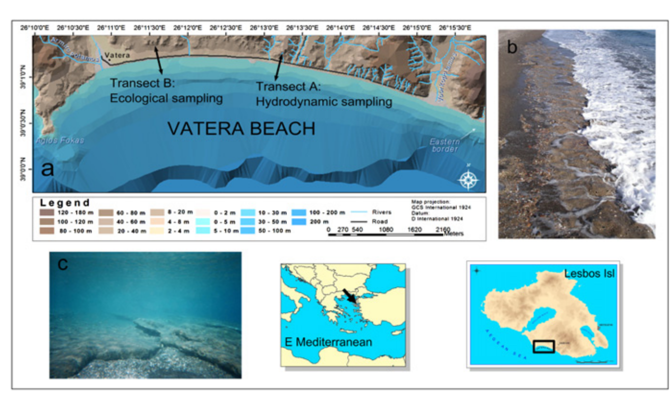

Fig. 1. Map of Vatera beach (Lesbos, Greece) showing (a) the monitored transects A (hydrodynamic sampling) and B (ecological sampling), (b) onshore and (c) submarine beachrock outcrops at Transect A.