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Seeking harmony in coastal development for small islands: Exploring multifunctional artificial reefs for São Miguel Island, the Azores

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A B S T R A C T

The Azores is a remote archipelago rich in biodiversity, geodiversity and cultural heritage located in the middle of the North Atlantic Ocean. It comprises nine volcanic Small Islands (SIs) scattered over 600 km and are vulnerable to coastal hazards due to limited land availability and ocean exposure. To mitigate and adapt to hazards and human occupation, traditional hard-engineering structures have been used. However, these structures have negative impacts on natural coastal character and amenity value and with growing environmental awareness, soft-engineering solutions designed to work with natural processes, such as multifunctional artificial reefs (MFARs), are globally becoming more appealing. MFARs are offshore submerged structures which provide coastal protection while enhancing marine and recreational amenities such as surfing, diving and beach widening. This paper determines "optimal" MFAR multifunctional design criteria based on current progress and assessment of nine international MFARs installed to-date. It subsequently explores MFAR feasibility in São Miguel Island, the biggest and most populated Azorean Island with the largest surfing population. An assessment of surf breaks was undertaken, including coastal processes and retreat rates, and MFAR site selection, criteria and rationale are discussed. By considering site-specific parameters such as local bathymetry, wave climate, tides, coastal processes and marine environment alongside tourism potential and surf culture, São Roque reef was selected as a potential MFAR to provide both coastal protection and surfing amenity.

Introduction: the Azores, coastal hazard, anthropogenic impacts and coastal protection options

The Azores archipelago, a Portuguese autonomous region, is located in the North Atlantic approximately 1500 km from Lisbon and 3900 km from the east coast of North America. Consisting of nine Small Islands (SIs) of volcanic origin scattered over 600 km of ocean and aligned approximately WNW–ESE, it rises from a 2000 m deep plateau with mostly steep submarine slopes and relatively few shallow shelves (Fig. 1). The Azores archipelago encompasses an area of 2333 km^2 and a population of 246,772 according to 2011 census data (INE, 2011). Despite its small size, it has an Exclusive Economic Zone (EEZ) of *circa* 984,300 km^2 (Borges, Cabral, & Andrade, 2009), with the potential of a larger jurisdictional area on the continental shelf subject to recent Portuguese claims to the Commission on the Limits of the Continental Shelf (CLCS) to extend its continental shelf limits (CLCS, 2010). Diverse coastlines are predominantly low to high rocky cliffs with bluffs, dunes, lagoons and scattered pocket beaches. These SIs are vulnerable to coastal hazards due to limited land availability and ocean exposure. Seven generic coastal environmental hazards posing significant threats to Azorean coasts were projected by Calado, Borges, Phillips, Ng, and Alves (2011): sea-level rise, storms, coastal erosion, tsunamis, landslides, flooding, and seismic activity and volcanoes. High risk zones and corresponding mitigation or adaptation measures in each Island were also indicated in coastal zone management plans developed for each Island. Long fetches that characterize the ocean around the Azores result in high-energy

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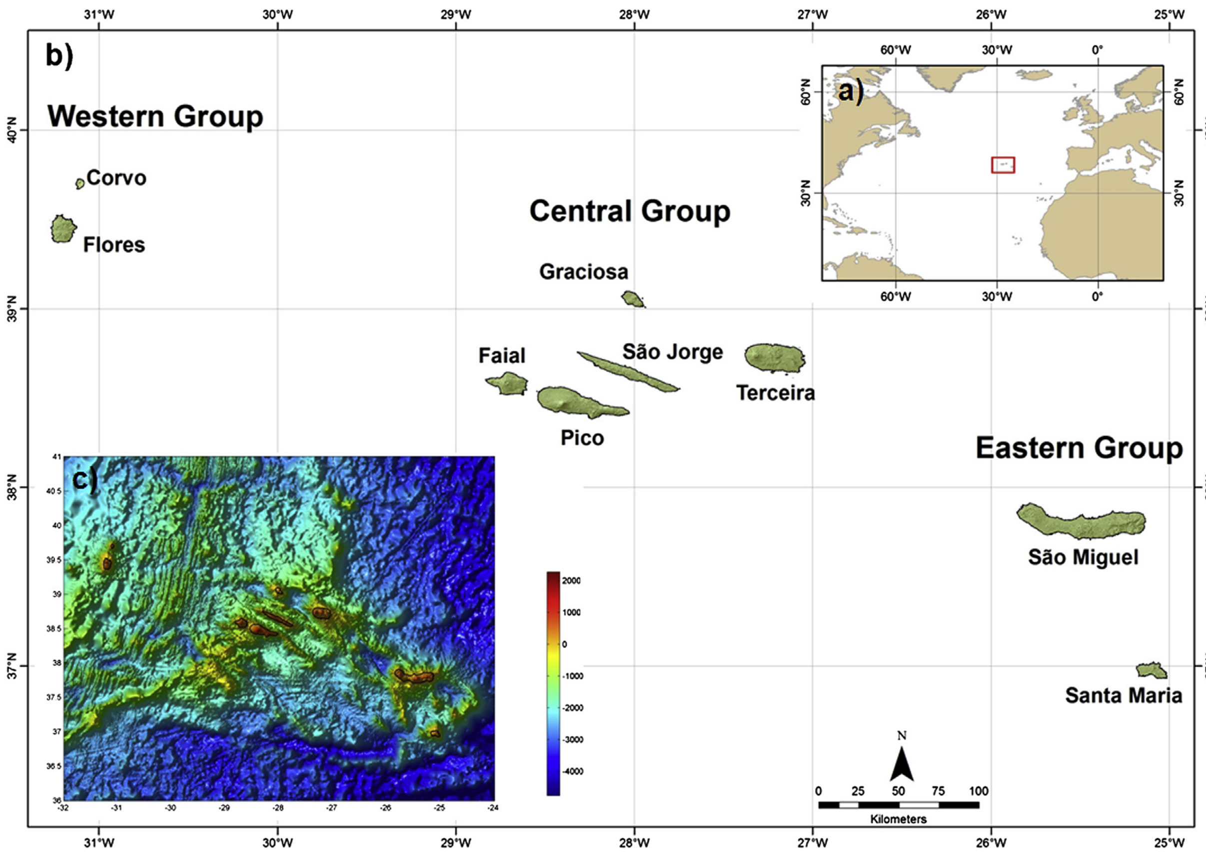

Fig. 1. Study area locality: a) map showing the Azores Islands (circled red) in relation to North Atlantic Ocean; b) map showing the Azores archipelago and c) bathymetric map of the Azores area, Smith and Sandwell (1997). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

wave climates where both sea and swell are sources of coastal energy, with the northern-facing shore of each Island in general being more exposed (Borges, Andrade, & Freitas, 2002). Some Azorean coastlines are particularly vulnerable to erosion, storms, flooding and landslides. The recession rates for bluffs are 0.2–1.0 $m\,yr^{-1}$ and 0.05–0.10 $m\,yr^{-1}$ for rocky coasts, with similar erosion rates for the north and south coasts (Borges, 2003). There is limited coastal erosion research, although further information can be found in Borges, Cruz, and Andrade (1997), Borges, Andrade, Cruz, and Marques (2001), Borges et al. (2002), and Borges, Lameiras, and Calado (2009). The mesoscale Azorean coastal erosion rates may appear insignificant in comparison with other low-lying regions, however, it is important to note that in relation to the Azores's relatively small land size, these rates represent a reduction on already limited land availability.

Despite the presence of extreme coastal hazards, most Island populations and economic activities cluster along the coasts as Azoreans are strongly dependent on the sea for their livelihoods, communication and trade. This is further accentuated by the narrow coastal fringe of the Azores Islands being one of few land areas that offers settlement potential. Commercial facilities and employment opportunities, together with economic activities and population, are thus located along the coasts. Over the last two decades, in line with the economic objectives, social and economic growth has resulted in accelerated coastal development including communication infrastructure, buildings and tourism facilities. Economic development has provided the financial means for Azoreans to buy residential and/or holiday homes along the coasts. However, these developments have also imposed intense socio-economic pressures in some coastal regions. Developers rush to meet demands, while inadequate planning and lax monitoring often result in detrimental coastal environment impacts. Neglecting environmental impacts and allowing over-stressing by human activities have caused threats to coastal systems and inhabitants. According to Calado et al. (2011), some of the main concerns include: changes to drainage networks; soil erosion due to elimination of vegetation cover; building too close to the coast; and developing on unstable coastal cliffs.

To mitigate and adapt to these hazards and human needs, various measures have been implemented in some of these threatened areas. These range from traditional hard-engineering structures such as seawalls, revetments, groins and detached emerged breakwaters to netted cliffs, small-scale beach nourishment, enlargement of buffer zones into public land, and as a last resort, relocation of residences and facilities. However, some conventional hard structures were often a short-sighted response to alleviate immediate problems and do not address the cause. When using hard structures it is difficult to preserve natural coastal character and amenity values, while achieving negligible downstream coastline impacts. In reality, although hard structures such as seawalls protect the area landward of the coast they frequently cause negative seaward impacts such as beach narrowing from the loss of natural shoreline resilience to the wave climate.

With greater environmental awareness, these intrusive and aesthetically unpleasing structures are becoming less appealing (Black & Mead, 2001). However, a relatively recent soft-engineering approach known as multifunctional artificial reef (MFAR; also commonly known as multipurpose reef or artificial surfing reef) are designed to work with nature by reducing wave impact on the coast (Black & Mead, 2001; Mead & Black, 1999). Their growing