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On the applicability of empirical formulas for natural salients to Sardinia (Italy) beaches

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ABSTRACT

The paper presents an empirical analysis of the shoreline response to natural obstacles, either submerged reefs and islands, distributed along the Sardinian (Italy) coastlines exposed to different wave and wind climates. The study focuses on salient morphological features whose geometrical properties have been acquired through an extensive field and image-derived survey. The current analysis has been used to propose geometric predictive formulas for stable salients that overcome some limitations affecting previous works. A semi-probabilistic method based on well-known rate-of-change statistics is also presented to verify the equilibrium condition of salients. Analysis results suggest that site-specific wave transmission in the lee of submerged reefs requires a range of salient limiting B/S ratio values broader than those presented in the literature, B being the length of the obstacle and S the distance between undisturbed beach and obstacle. The B/S ratio has been proved to be the main dimensionless variable for predicting salient amplitude and basal width. In particular, the proposed predictive equation suggests an erosion condition for some combinations of B/Sand the "8 times rule" appears not to be applicable to natural salients.

1. Introduction

Shore-parallel structures in the form of rubble-mound emergent breakwaters located within the surf zone are the most common protective structures for limiting shoreline erosion or for promoting beach widening. In contrast, fully submerged (Ranasinghe and Turner, 2006) and low-crested (Lamberti and Zanuttigh, 2009) structures have only rarely been adopted for beach protection. A critical aspect in the design of these breakwaters is the prediction of the effects of the structures on the shoreline. Often, incorrectly dimensioned breakwaters can result in the formation of an unwanted tombolo and/or an eroding downdrift beach. Engineers and scientists have predicted long-term shoreline evolution in the lee of an offshore obstacle primarily using a) physical models, b) models based on the conservation of sand volume equation (one-line models), c) coastal morphodynamics models, and d) empirical models. Physical models (see e.g. Mory and Hamm, 1997) are well-suited to local analysis but are cost prohibitive to use for very large scales and their applicability is constrained by scaling problems for the sediment. The conservation-of-sand-volume approach, also known as the "one-line approach", has become the preferred modeling approach for evaluating shoreline change that could result from anthropogenic or natural changes in the beach and seaward salients system present in a coastal area. All one-line models assume the beach profile shape remains constant, the shoreward and seaward vertical limits of the profile are constant, the sand is transported alongshore by the action of breaking waves and longshore currents, the detailed structure of the nearshore circulation is ignored, and there is a long-term trend in shoreline evolution due to an infinite supply of sand. Examples of one-line models are GENESIS (Hanson and Kraus, 2011) or LITPACK by DHI. Numerical models of the equations of shoreline and beach motions are implemented in models of coastal morphodynamics in simple or more complete form, but these require large computational resources and are not well-suited to the large spatial and temporal scales over which beaches and nearshore salients evolve. These coastal morphodynamic models are further subdivided into two-dimensional horizontal models (e.g. Ranasinghe et al., 2006), which use depth-averaged equations, and three-dimensional models (e.g. Lesser et al., 2004), which resolve the vertical variations in flow and transport. Large differences exist in the type of wave, flow and sediment transport models applied, the frequency of updating, numerical bed updating schemes and morphological acceleration techniques. Roelvink and Reniers (2011) provide a review of different numerical schemes implemented in these models, with an in-depth discussion of strong points and hindrances of the each model for simulating different coastal processes. Empirical models are formulated as simple relations between the obstacle geometry and the resulting shoreline evolution. To define empirical predictive formulas, models use wave diffraction theoryto predict an

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equilibrium shoreline (Hsu et al., 2003), and are based on analysis of field data (Hsu and Silvester, 1990) or results from numerical models (Hakeem et al., 2010). Empirical predictive formulas are reasonably in agreement with numerical model results (Kristensen et al., 2013)and can provide a complementary tool with morphodynamic models that uses implified input data to obtain reliable results, as demonstrated by Sulis and Annis (2014) in the application of the uncoupled morphological model of the package MIKE 21 FM (DHI, 2008) to the shoreline stability of a salient in the lee of an emergent natural reef at Sa Mesa Longa (Sardinia).The ability of empirical predictive formulas to predict the characteristics of shoreline salients has a clear engineering relevance. Practicing engineers often have to provide solutions to beach protection and these empirical formulas can provide a conservative approach to the preliminary characterization of the shoreline evolution behind the designed structure. Therefore, the empirical approach is not intended to support further engineering design in more advanced levels as, at that step, detailed field survey data are available to feed accurate morphodynamic models. The practical utility of these predictive equations is in assisting coastal engineers to roughly estimate the geometric values of the main governing parameters at a preliminary design level (Hsu and Evans, 1989).

Shoreline salients are often observed in the lee of natural reefs located in the nearshore region. To date, no systematic studies on the effects of natural obstacles, either submerged reefs or islands, have been undertaken along the Mediterranean coasts to provide empirical predictive formulas. Particularly, reasonable quantitative relationships for determining the geometrical properties of shoreline adjustment to natural obstacles are lacking. Black and Andrews (2001) defined criteria for salient formation and empirical relationships to describe the morphology of salients and their geometries by visually inspecting aerial photographs of the coastlines of southeastern Australia and New Zealand. However, some of the conclusions from this study are counter-intuitive, and Ranasinghe et al. (2006) indicated several shortcomings. The most obvious shortcoming of the predictive empirical relationship proposed by Black and Andrews (2001) is that erosion is not predicted to occur for any combination of obstacle dimensions.

Within a broader research program on coastal erosion funded by the Sardinian government, the University of Cagliari (Sardinia, Italy) has been acquiring data at different levels of detail and accuracy (using new field survey technology such as the Real-Time Kinematic Global Positioning System(RTK-GPS), and an image-derived survey method based on aerial and IKONOS satellite imagery) from the main salients along the coastlines of Sardinia, the second largest island of the Mediterranean Sea. We are not aware of any prior extensive survey of these morphologies in the Mediterranean Sea and the paper presents the first database that maps the main properties of salient geometry and processes affecting their evolution. The objectives of this paper are to verify the equilibrium condition of shoreline behind natural emergent and submerged natural obstacles using the proposed semi-probabilistic method based on rate-of-change statistics, and to propose and validate predictive formulas for geometric properties of salients in equilibrium conditions along the Sardinian coastline, that overcome some limitations affecting previous works. By investigating the characteristics of natural obstacles and associated shoreline salients in Sardinia, the paper aims to provide practical insight into shoreline responses to engineered submerged structures that could be of value for coastal engineers and managers operating in the Mediterranean Sea where the wave climate and tide differ significantly from ocean conditions.

The paper is structured as follows. First, it summarizes field and image-derived surveys. Secondly, the shoreline analysis applied to a time series of digital shoreline position data is presented. In the framework of a semi-probabilistic model for shoreline change, two criteria are used to ascertain whether the salient has reached its equilibrium condition. Then, the paper extensively describes the model through its application to a salient located at Maladroxia beach (southwestern Sardinia). The next section summarizes the analysis of the equilibrium conditions of all selected salients along the Sardinian coastline. The results of these investigations on the development of a predictive relationship for shoreline response to natural obstacles are discussed. Finally, specific knowledge gaps that require further research are identified in the conclusions.

1.1. Study site and data description

Sardinia is the second biggest island in the Mediterranean Sea. It has a wet season (October to April) accounting for 80% of the yearly precipitation with increasingly frequent heavy rainstorm events, and a dry season (May to September). The hydrographic service of the Italian Institute for Environmental Protection and Research (ISPRA) owns and manages the national networks of tide gauges (RMN) and data buoys (RON). Since 1986, RMN in Sardinian has been composed of three measuring stations with ultrasonic transducers located inside the harbors at Cagliari (south coast), Carloforte (southwest coast) and Porto Torres (north coast) (Fig. 1). Tide data reveals that the area is a microtidal coast with small differences between the three gauges. The data show astronomical mean spring and neap tide a range over the period 1988–2013 of approximately 0.30 m and 0.15 m, respectively, and an extreme storm surge value of approximately 0.50 m, with a return period of 100 years. Three Triaxys wave buoys have been deployed offshore from the Sardinian coasts to collect wave data continuously and provide synthetic and spectral parameters (Fig. 1). With the exception of the Alghero buoy (northwest coast) that covers the period between 1989 and 2008, data from the Cagliari and Capo Comino buoys (northeast coast) are not statistically significant. When not available from the RON dataset, data extracted from the “Wind and Waves Atlas of the Mediterranean Sea” (MEDATLAS, 2004) and the Institute of Marine Sciences of the Italian National Research Council (ISMAR-CNR) study (ISMAR-CNR, 2004) were used in this study. The Atlas contains bivariate tables of annual and seasonal frequency distributions of wave data (significant wave heights versus mean direction or peak period) resulting from a 10-yearhindcast based on a WAM model simulation calibrated with satellite altimeter measurements over a grid with a resolution of 1degree. In the case of the ISMAR-CNR wave dataset, a specific implementation of the WAM model was run at the ISMAR-CNR using the wind analysis and forecast fields from the European Centre for Medium-range Weather Forecast (ECMWF) as forcings with different meteorological model resolutions whose outputs were compared with altimeter and buoy data (Cavaleri and Bertotti, 2003). A Peaks-Over-Threshold time series was provided for 10 years over 6-h intervals. The ISMAR-CNR wave dataset was used for beaches along the south coast. Fig. 1 shows the points along the Sardinian coasts considered in this study.

The geology along the Sardinian coastline varies, including both rocky coasts and low-lying sandy beaches. Most Sardinian beaches are remnants of the large sandy shoreline formed during the last glacial stage (Manca et al., 2013). At that time, lower sea levels resulted in erosion that uncovered the marine shelf sediments, which were then blown landward to form the main coastal dune systems and sandy deposits that characterize the western coast of Sardinia. The beaches are at risk of coastal flooding and erosion (Ginesu et al., 2016). Using digitized shorelines extracted from 1:25,000 scale maps and aerial photographs, a recent report indicated that 14% of the beaches have retreated at least 25 m in the past 50 years (ISPRA, 2010). Dunes are an important feature of Sardinia's coastlines and are usually fronted by wide sand beaches. Approximately 500 km of plains near the coastline are occupied by Quaternary deposits, principally aeolian sands. Being mostly relict features, the equilibrium of aeolian deposits is very sensitive to both climatic and anthropogenic factors (French et al., 1995). In the1960s, a phanerophyte native to Australia was introduced mainly in the coastal areas in Sardinia for afforestation. Currently, this area is considered naturalized, having become invasive in dunal habitats. *Posidonia oceanica* is a marine phanerogam endemic to the