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A coastal erosion model to predict shoreline changes

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ABSTRACT

Coastal erosion is a natural phenomenon affecting a growing number of worldwide sites. The impact of the waves on coast is cause of debris removal and soil erosion. The effect depends on wave strength, action time, and wave direction. In literature, several models have been proposed to estimate the mean rate of sediments moved annually alongshore. In the manuscript, the authors propose a prediction model to estimate the evolution of shoreline due to coastal erosion. Three altimeters are used to measure the instantaneous sea surface elevation. Directional wave spectrum is computed in order to estimate the direction of wave propagation and its measurement uncertainty. The shoreline is discretised into a finite number of linear segments. Then, according to historical information on the shoreline transformation, the impact of the wave on the coast is evaluated. Subsequently, the model predicts the changes of each line segment estimating the future shoreline.

1. Introduction

Seaquakes, floods and coastal erosion are some effects of water impact on the soil. Such phenomena are due to large amounts of water colliding strikingly with earth. In such cases, water can be even cause of catastrophic events which shape the coast and the environment. The manuscript deals with coastal erosion issue and with prediction of shoreline changes. Such phenomenon is not caused only by sudden and extreme sea storms, but it is the consequence of the natural and continuous effect of the wave impacting against the coast. Consequently, attention is mainly turned on monitoring near-shore wave movements in sea and ocean. In literature, probabilistic models based on analyzing historical time series are widely used. Such solutions are cheap, however prediction results are often inaccurate and incomplete. Differently, coast monitoring systems are important tools in order to predict accurately planform and profile evolution of beach. So, real-time data concerning wave elevation and propagation have to be acquired. To this aim, near-shore sensor networks are commonly used to get timely measurements of the sea state [1–8]. Nevertheless such sensor networks suffer of synchronization problems [9,10]. In these cases, the wave impact on the coast is investigated by analyzing the directional wave [11]. Information on the direction of wave propagation is thus used to estimate the debris removal and the coastal erosion. About this issue, different models and procedures have been proposed in literature. For instance, surface buoys with mounted measurement equipment such as altimeters [1–4], and wave radar are frequently used for measuring wave elevation in near-shore and off-shore regions [12,13]. Even satellite image processing techniques based on segmentation algorithms have been proposed [14,15]. Nevertheless measurements are often inaccurate entailing false alarms or underestimations of hazard events (see Fig. 1).

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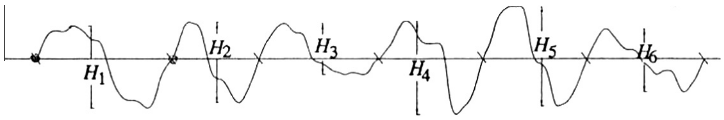

Fig. 1. Wave elevation record.

The authors propose an innovative approach to predict the coastal erosion evolution. It is based on a model previously developed in [16], which is able to estimate the direction of wave propagation by means of elevation measurements. The direction of wave propagation is an important parameter to estimate the sediment transport. Measurement systems used in the practice are commonly based on wave-gauges or altimeters. Sensor networks or arrays are among the most widely proposed solutions for wave direction measurements. Buoy data are processed to get information about spectrum peak direction and incidence angle [17–19]. However, measurement uncertainty is often not considered during data processing. In the model proposed, the authors entail with this issue [16]. The directional wave spectrum is estimated to characterize wave movements and the sea state [20–24].

The impact of wave on the beach and the resultant erosion result depend on several factors such as the strength, the action time, the type of soil and mainly on the direction of propagation. Waves are mostly generated by the wind. In the beginning of generation, wave crests are very short and typically waves move in many directions. With the growth stage, waves propagate in the wind direction and the crests become longer. Wind waves typically leave the generation area becoming swells. The last ones cover long distances and are long-crested waves. In this sight, the direction of propagation of wind waves is easily estimated by considering the wind direction. Differently, more attention has to be paid on swells. So their representation in terms of directional spectrum is a basic approach to this issue. During motion, when wave is approaching to the coast, its energy disperses due to different factors such as sea depth variation or currents. Information on wave propagation angle is therefore used to optimize the prediction of the beach planform evolution. An innovative model starts from the current shoreline of the monitored coast. It is discretised into a finite number of linear segments. Then, according to historical information on the shoreline transformation and on the direction of wave propagation, the model predicts the changes of each line segment so to derive the next shoreline. A map of the beach profile evolution is depicted to compare the time trend and the level of coastal erosion risk.

2. Estimation of wave propagation direction

Waves are principally originated by wind. The main factors which have influence on the size of wind waves are the wind speed and its duration, water depth, and the extent of sea surface affected by wind. The ideal sea state can be characterized by means of a sequence of wind waves in an undefined time interval with stationary state. Differently, the real sea state can be characterized by means of a discrete number of consecutive waves $N \approx 100$–300. Such number is optimal to consider the state as stationary and representative of the sea conditions. With this assumption, the real sea state can be considered as a subsequence of the ideal one. Assume to consider a specific point of the sea. After a time, waves start to generate. They can be wind waves or swells. In detail, when the waves are directly due to local winds, we refer to wind waves. If the waves are not generated by local wind at that time, we refer to swells, so such waves have been generated elsewhere, or some time ago. Let us consider a buoy network in the sea being able to perform wave measurements at near-shore [1–4]. Each boy mounts on board an altimeter. So, we have to consider a record of the wave elevation η in the fixed point of the sea.

This parameter changes with the time. So $\eta(t)$ is the vertical displacement of the wave free surface referred to the undisturbed average level. Each wave can be characterized as the portion of $\eta(t)$ between two consecutive zero upcrossings with the same slope. The period of the wave is the time interval between the two consecutive zero upcrossings. The crest and trough are the points on a wave with the maximum and minimum values respectively. The wave height is the vertical difference between the trough and the crest. The wavelength is the time interval from crest to crest.

Suppose to consider several records $\eta_i(t)$ of the wave vertical displacement acquired by the buoy in the considered point of sea. Each record represents a real sea state with N waves. According to the *first-order Stokes theory* of sea state, the time series $\eta_1(t), \eta_2(t), \ldots, \eta_n(t)$ are events of a stochastic stationary Gaussian process. Each event has an infinite time interval, so it represents an ideal sea state and can be described by the equation:

$$\eta(t) = \sum_{i=1}^{N} a_i \cos(\omega_i t + \varepsilon_i) \tag{1}$$

The ith element of the summation represents the vertical displacement of the wave free surface with amplitude a_i, angular frequency ω_i and phase ε_i. The sea state theory assumes that:

- $N\infty$;
- ε_i values are stochastically independent and distributed over a round angle;
- ω_i values are unequal each other;
- a_i values are infinitesimal.

In order to estimate the line spectrum of the wave elevation, we have to consider time series $\eta_1, \eta_2, \ldots, \eta_n$ with n being an odd number, where $t_1 = 0$, $t_2 = \Delta t_{camp}$, ..., and $t_n = (n-1)\Delta t_{camp}$. The Fourier series $\eta_F(t)$ is obtained by