

A NEAR-SHORE WAVE MONITORING MODEL FOR BEACH PLANFORM EVOLUTION PREDICTION

R. Morello, C. De Capua and F. Filianoti

Dept. DIIES, University Mediterranea of Reggio Calabria, Reggio Calabria, ITALY

Abstract: Coastal erosion is a serious problem affecting a growing number of sites worldwide. Frequently, the erosion is caused by long-shore drift currents induced by sea waves in the surf zone. Many formulas have been proposed by researchers in order to estimate the mean rate of sediments moved annually alongshore by waves. In the present paper, the authors describe a revised model for predicting the long-shore drift current. The model is based on directional wave analysis by means of measurements of the instantaneous sea surface elevation operated simultaneously by three altimeters closed each other in a non-colinear configuration. Such information is used to characterize the waves forming a sea state. Time series measurements of water surface elevation are analysed. So directional wave spectrum is computed in order to predict the mean angle of advance of waves. The model has been improved and optimized by considering the effect of measurement uncertainty in the wave direction estimation. As a consequence, the wave propagation direction is accurately evaluated so to produce a reliable prediction of the long-shore current.

Keywords: coast erosion; sea state; monitoring; directional wave spectrum; measurement uncertainty; wave propagation direction.

1. INTRODUCTION

The earth surface is covered with about 71% of water. Seas, oceans and lakes are a clear demonstration of that. Although water is a vital element for life, it is cause of unwanted phenomena and even of hazard events. So, for instance, seaquakes and floods are some catastrophic phenomena impacting on earth due to water movements. Nevertheless further natural events like coast erosions and the elevation of sea level represent current processes due to climate changes. In the present manuscript, attention is turned on near-shore wave movements in sea and ocean. Coast monitoring systems are important tools in order to predict planform and profile evolution of beach. Such systems require real-time data concerning wave elevation and propagation. To this aim, near-shore sensor network are commonly used to get timely measurements of the sea state, [1]-[4]. Nevertheless such sensor networks suffer of synchronization problems, [5], [6]. Directional wave and current measurements are analysed in order to predict the possible wave impact on the coast, [7]. In these cases, the wave propagation direction is estimated to study the wave

motion and the consequent coast erosion. Different models and procedures have been proposed in literature. Operational systems that provide real-time data, surface buoys with mounted measurement equipment such as altimeters, [1]-[4] and wave radar have been used for measuring wave elevation in near- and off-shore regions, [8]-[10]. So several technologies have been used in literature for environmental monitoring, such as radar applications or satellite image processing techniques with segmentation algorithms, [9]-[11]. Nevertheless measurements are often inaccurate entailing false alarms or underestimations of hazard events. Many challenges remain still open. Surely, wave propagation direction is an important parameter. It is used not only to predict possible alarm occurrences but also to resolve engineering problems such as the estimation of sediment transport and the response of coastal structures. Measurement systems used in the practice are commonly based on wave-gages or altimeters. A sensor network or array configuration is among the most widely proposed solutions for wave direction measurements. Computing based on three-gage arrays have been proposed by many researchers. It offers some advantages in respect to networks with a larger number of sensors; economic benefits are surely one of these advantages. Buoy data are processed to get information about spectrum peak direction and incidence angle, [12]-[14]. However, measurement uncertainty is often not considered during data processing. So the authors entail with this issue. The directional wave spectrum is an interesting tool to estimate and model wave movements and the sea state. In order to use a methodological approach, we have to start from the wave generation mechanism. Waves are mostly generated from 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 becomes 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 propagation direction 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, [15]-[19]. During motion, when wave is approaching to the coast, its energy disperses due to different factors such as sea depth variation or currents. The analysis of wave directional field data is a complex issue. Often coast monitoring systems are based on empirical data or unreliable measurement data, so numerical

approximations or simulations are performed. Real time wave monitoring is the best solution for beach platform evolution prediction applications.

The authors have previously developed several applications in environmental monitoring field, [20]-[24]. In the present manuscript a near-shore buoy network is considered. The authors propose a revised model for directional wave analysis. The model has been improved by considering the effect of the measurement uncertainty on the estimation of wave propagation direction.

2. WAVES AND SEA STATE

Near-shore and off-shore wave measurements are typically performed for coast surveillance purposes or for prediction of coast erosion evolution over time. So wave elevation models are based on measurements done from surface wave buoys. They are a solution commonly used to make continuous monitoring campaigns in order to detect timely seaquake or coast corrosion phenomena. Let us consider a buoy network in the sea being able to perform wave measurements at near-shore, [1]-[4]. Each buoy mounts on board an altimeter. Fig. 1 shows a record of the wave elevation η in a fixed point of the sea.

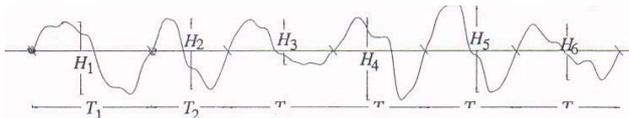


Fig. 1. Wave elevation record.

This parameter changes with the time. So $\eta(t)$ is the vertical displacement of the wave free surface referred to the undisturbed average level. Generally waves have different shapes and features. So we can define some specific features of wave motion. In detail each single wave can be characterized as the portion of $\eta(t)$ between two consecutive zero up-crossings with the same slope. The period of the wave is the time interval between the two previous zero up-crossings. The crest and trough are the points on a wave with the maximum and minimum value respectively. The wave height is the vertical difference between the trough and the crest, [7]. The wavelength is the time interval from crest to crest, see Fig. 2 for reference.

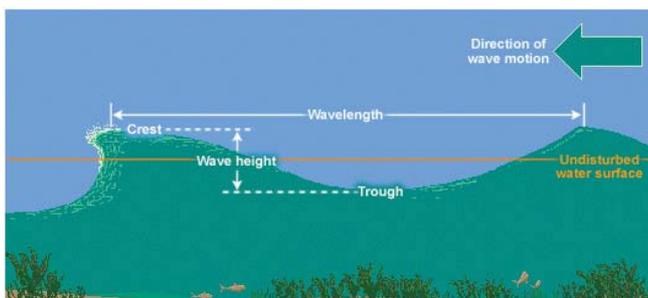


Fig. 2. Wave characteristics.

Waves are principally originated from 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. In the present work, the authors focus the attention on the wave propagation direction for coast erosion prediction. The ideal sea state can

be characterized by a sequence of wind waves in an undefined time interval with stationary state. In other words, we can start from the ideal sea state to obtain the real one. Suppose to consider several sets of N consecutive waves. For each set, the average wave height and period are computed. If the number N of waves is low, the averaged wave heights and periods of the sets will be different each other. With the increasing of N , such differences decrease. For $N \rightarrow \infty$ the sea state will be uniform for each set. Differently, the real sea state can be characterized by 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. And in particular, the wave height and period in the real case are most likely equal to the values of the ideal case. 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 due directly to local winds we refer to wind waves. If the waves are not generated from local wind at that time, we refer to swells, so such waves have been generated elsewhere, or some time ago. Suppose to consider several records $\eta_i(t)$ of the wave vertical displacement acquired from the buoy in the considered point of the sea. Each record represents a real sea state with N waves. According to the first-order Stokes theory of sea state, the time series $\eta_1(t)$, $\eta_2(t)$, ..., $\eta_n(t)$ 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:

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

The i -th 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:

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

Let $E(\omega)$ be the spectrum of the wave elevation

$$E(\omega)\delta\omega = \sum_i \frac{1}{2} a_i^2 \quad (2)$$

where it is $\omega - \delta\omega/2 < \omega_i < \omega + \delta\omega/2$, [25], [26].

With this assumption, equation (1) represents a stochastic stationary Gaussian process.

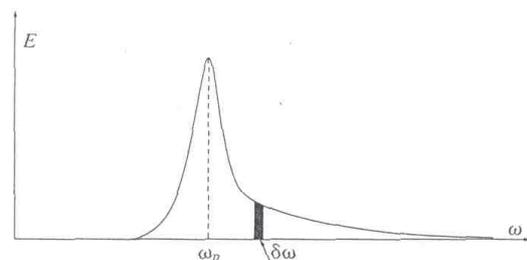


Fig. 3. Wave spectrum.

We can get information on the intensity of the sea movement by estimating the standard deviation on the whole duration of the sea state:

$$\sigma = \sqrt{\langle \eta^2(t) \rangle} \quad (3)$$

High values of σ indicate more intense vertical displacements of the wave free surface and in these cases the wave height is higher. The typical parameter used to estimate the displacement is the significant wave height:

$$H_s = 4\sigma \quad (4)$$

Let ω_p be the dominant angular frequency, or in other words the angular frequency of the spectrum peak. While T_p is the dominant period:

$$T_p = 2\pi / \omega_p \quad (5)$$

The autocovariance represents the average value of the wave elevation after a time interval equal to T :

$$\Psi(T) = \langle \eta(t)\eta(t+T) \rangle \quad (6)$$

As a consequence, the autocovariance changes with the T value. Therefore, in order to get a reliable estimation of the wave elevation of the sea state, we have to define the sampling time Δt_{camp} between two consecutive records. Experimental results have shown that optimal estimation are obtained with sampling time not higher than $1/15 \cdot T_p$.

So when the values $\eta_1, \eta_2, \dots, \eta_n$ of a real sea state are computed, it is possible to estimate the standard deviation by the expression:

$$\sigma = \sqrt{\frac{\eta_1^2 + \eta_2^2 + \dots + \eta_n^2}{n}} \quad (7)$$

and consequently we can estimate the significant wave height H_s .

Suppose that the recording time is equal to 10 minutes with a sampling frequency of 10 S/s. So we will get 6000 values of η ($\eta_1, \eta_2, \dots, \eta_{6000}$) with a duration of 0.1 s. If $T = 1$ s we can estimate $\psi(T)$ by the expression:

$$\Psi(1s) = \frac{\eta_1\eta_{11} + \eta_2\eta_{12} + \dots + \eta_{5990}\eta_{6000}}{5990} \quad (8)$$

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

$$\eta_F(t) = \sum_{i=1}^N a'_i \cos(\omega_i t) + a''_i \sin(\omega_i t) \quad (9)$$

with

$$\eta_F(t_i) = \eta_1, \dots, \eta_F(t_n) = \eta_n$$

$$N = (n-1)/2$$

$$\omega_i = \frac{2\pi}{\Delta t_{\text{camp}}} \frac{i}{n}$$

$$a'_i = \frac{2}{n} \sum_{j=1}^n \eta_j \cos(\omega_i t_j)$$

$$a''_i = \frac{2}{n} \sum_{j=1}^n \eta_j \sin(\omega_i t_j)$$

$$\text{and } \eta_F(t + T_p) = \eta_F(t)$$

So the Fourier series $\eta_F(t)$ can be computed by the equation:

$$\eta_F(t) = \sum_{i=1}^N a_i \cos(\omega_i t + \varepsilon_i) \quad (10)$$

Consequently the line spectrum $E_F(\omega)$ of $\eta_F(t)$ is given by:

$$E_F(\omega) = \sum_{i=1}^N \frac{1}{2} a_i^2 \delta(\omega - \omega_i) \quad (11)$$

3. THE DIRECTIONAL WAVE SPECTRUM

In order to analyse the wave propagation direction, we have to estimate the directional wave spectrum starting from the line spectrum in (11). To this aim, the authors starts from the model in [27]. It was applied successfully also in [28] during a small scale field experiment carried out directly at sea. This model considers three buoys or measurements points A, B and C as in Fig. 4.

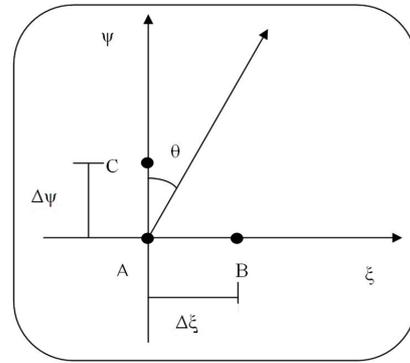


Fig. 4. Wave propagation direction.

In each point, an altimeter measures the wave elevation. According to the model in [27], [28], the wave elevation in the three points can be estimated by the following equations:

$$\eta_A(t) = \sum_{i=1}^N a_i \cos(-\omega_i t + \varepsilon_i) \quad (12)$$

$$\eta_B(t) = \sum_{i=1}^N a_i \cos(k_i \Delta x \sin \theta_i - \omega_i t + \varepsilon_i) \quad (13)$$

$$\eta_C(t) = \sum_{i=1}^N a_i \cos(k_i \Delta y \cos \theta_i - \omega_i t + \varepsilon_i) \quad (14)$$

where k is the number of waves, and θ_i is the angle of the wave propagation direction. The previous equations can be rewritten in the following form:

$$\eta_A(t) = \sum_{i=1}^N A'_i \cos \omega_i t + A''_i \sin \omega_i t \quad (15)$$

$$\eta_B(t) = \sum_{i=1}^N B'_i \cos \omega_i t + B''_i \sin \omega_i t \quad (16)$$

$$\eta_C(t) = \sum_{i=1}^N C'_i \cos \omega_i t + C''_i \sin \omega_i t \quad (17)$$

As a consequence, we can obtain the angle of the wave propagation direction:

$$\tan(k_i \Delta x \sin \theta_i) = \frac{A'_i B''_i - A''_i B'_i}{A'_i B'_i + A''_i B''_i} \quad (18)$$

or

$$\tan(k_i \Delta y \cos \theta_i) = \frac{A_i' C_i'' - A_i'' C_i'}{A_i' C_i' + A_i'' C_i''} \quad (19)$$

According to the linear theory of wind-generated waves in [27], [28], the angle of the wave propagation direction θ_i is got by estimating the quantities A_i' , A_i'' , B_i' , B_i'' , C_i' , C_i'' . By resolving the equations (18) and (19) respectively, the solution is one if $k_i \Delta x < \pi$ or as an alternative $k_i \Delta y < \pi$. Two solutions are possible if $\pi < k_i \Delta x < 2\pi$ or as an alternative $\pi < k_i \Delta y < 2\pi$. We have more of one solution if $k_i \Delta x > 2\pi$ or as an alternative $k_i \Delta y > 2\pi$. In brief, the solution for θ_i is unique if Δx and Δy are smaller than π/k_i , so that

$$\theta_i = \arcsin \frac{\arctan \frac{A_i' B_i'' - A_i'' B_i'}{A_i' B_i' + A_i'' B_i''}}{k_i \Delta x} \quad (20)$$

or

$$\theta_i = \arccos \frac{\arctan \frac{A_i' C_i'' - A_i'' C_i'}{A_i' C_i' + A_i'' C_i''}}{k_i \Delta y} \quad (21)$$

The above described model has been improved by considering the effect of the combined measurement uncertainty $u_c(\theta_i)$ on the wave propagation direction. According to the *Guide to the expression of Uncertainty in Measurement (GUM)* in [29], [30], if all input quantities are independent, the combined standard uncertainty can be evaluated by the expression:

$$u_c(\theta_i) = \sqrt{\sum_{j=1}^M \left(\frac{\partial f}{\partial z_j} \right)^2} u^2(z_j) \quad (22)$$

where z_j is the generic variable and M is the number of variables.

So the estimated wave propagation direction is affected from uncertainty. As a consequence its real direction can change within an angular interval whose value is equal to $\theta_i \pm u_c(\theta_i)$.

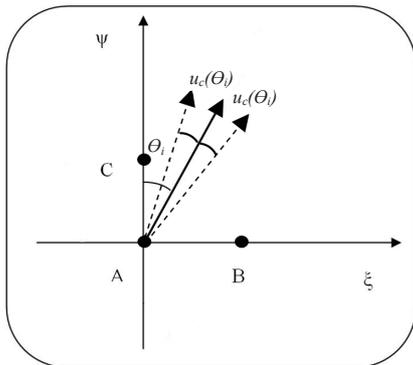


Fig. 5. Revised wave propagation direction.

In this way, it is possible to estimate accurately the wave propagation direction according to the available information on the uncertainty of the measurement instrumentation. The aim of the proposed revised model is to optimize the directional near-shore wave analysis for applications of beach profile evolution prediction.

4. CONCLUSION

In the paper, the authors have proposed a revised directional wave spectrum model in order to predict accurately wave propagation direction. The model is based on computing buoy measurements. Altimeters provide a measure of the wave elevation. The vertical displacement of the wave free surface is so used to estimate the directional wave spectrum. Nevertheless, uncertainty affecting measurements can be cause of errors and inaccurate estimation of the wave propagation direction. As a consequence, this can involve an erroneous interpretation of the coastal erosion process. Therefore, the model has been improved by considering the effect of the measurement uncertainty. In this way, the revised model provides a measure of the real wave direction within an angular interval so improving the accuracy of estimation. Future work concerns the development of a sensor data fusion procedure to optimize the data processing stage, [31], [32]. The authors are at the moment working on the project of a smart sensor network able to perform automatically the proposed model, [33]-[35].

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