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A MODEL TO MONITOR SEA STATE FOR PREDICTING PROPAGATION OF POLLUTANTS IN SEA AND OCEAN

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Abstract: Water pollution is a serious problem affecting rivers, seas, oceans and natural water resources. Pollution can be caused by human activities or as undesired consequence of an incident or natural disaster. The prediction of the propagation direction of contamination could support the decontamination activities in order to be more effective. By considering the disastrous effects on fauna and flora, attention is paid on oily contaminants, such as petroleum and oils, in sea and ocean. Such contaminants can be even not-visible at naked eye.

In this paper, the authors describe a revised model to predict the wave propagation direction so to evaluate the pollutant propagation. The model is based on the directional wave analysis. A buoy network equipped with altimeters is used to measure the instantaneous sea surface elevation. Time series measurements are processed to evaluate the directional wave spectrum. Consequently, the propagation angle of wave, and therefore the pollutant propagation, is predicted. The measurement uncertainty contribution is computed in order to optimize the estimation of the wave propagation direction.

Keywords: oily contaminants; sea pollution; sea state; directional wave spectrum; wave propagation direction; water pollution monitoring.

1. INTRODUCTION

Water contamination monitoring is a really complex task. Several human activities are cause of undesired pollution of water as a consequence of incidents and disasters. Chemical refineries and industrial plants make a large use of compounds which are polluting. Leakage of such contaminants may happen not just only for incidents, but may be even the effect of a natural disaster. Seaquakes and floods are just two examples of catastrophic natural phenomena which can impact on plants and consequently convey polluting substances. Depending on the specific pollutant, several decontamination techniques exist. To this aim, it is important to evaluate the propagation direction of the contamination in order to make the decontamination activities more effective. The evaluation or prediction of the pollution propagation is made more difficult if we consider an extended area such as oceans and seas. The complexity of water contamination monitoring is more clear if we observe that about 71% of earth surface is covered by water.

In this paper, attention is focused on oily contaminants, such as petroleum and oils, which can be even not visible at naked eye. In Figure 1, the consequence of petroleum contamination on sea is shown.

Fig. 1. Sea and ocean contamination.

The consequent effects on fauna and flora may be disastrous. Figure 2 shows a possible consequence of petroleum contamination in sea.

Fig. 2. Contamination effects on fauna.

The decontamination process is made particularly complex because of the properties of this kind of oily contaminant which floats on water surface and propagates according to the wave movements. In detail, the direction of

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propagation is due to wave action both near-shore and off-shore. In addition, the propagation direction can change suddenly and quickly with the changes of wave movement. In order to understand the contamination propagation mechanism, we must study the wave generation phenomenology. Waves are mostly generated from the wind. During the primary stage of generation, waves can move in several directions and crests are short. With the constant and continuous action of wind, the wave swells and its propagation direction aligns with the wind direction. In this stage, the wave is named ‘wind wave’ and the crests become longer. When the wind wave leaves the generation area due to wind action it becomes a ‘swell’. A swell can propagate for long distances with long-crested waves. As a consequence, information on wind propagation direction can be used in order to evaluate the direction of wind waves, but it is not enough to evaluate the direction of swells.

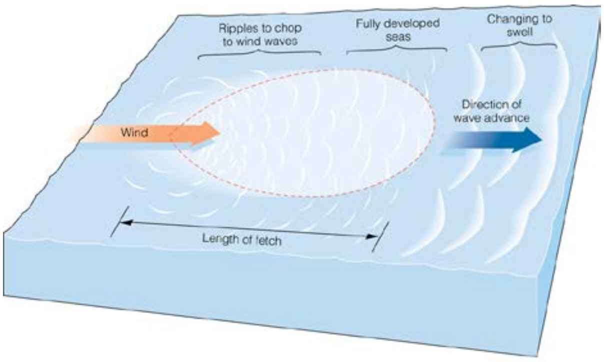

Fig. 3. Wind waves and swells [Brooks/Cole – Thomson 2005].

The study is focused on near-shore and off-shore wave movements in sea and ocean in order to predict the evolution of contamination propagation with time. The final aim is to support the decontamination activities by providing a methodological approach to the delimitation of the intervention area. Although the proposed approach could seem useless for contaminating oily compounds which are visible at naked eye, such as the petroleum, it provides more advantages for transparent contaminants.

Today, several technologies and methodologies could be used to simplify or assist the decontamination activities:

- surface buoys with multiparametric probes;
- undersea wave radar;
- satellite image processing techniques;
- near-shore and off-shore pollution monitoring systems;
- sensor network or arrays sensing specific pollutants;
- propagation simulation systems.

However, probes and sensors are able to provide only local information on the pollution of the monitored zone without providing a general overview of the pollution propagation. Satellite images fail when the pollutants are not visible at naked eye. Whereas, data based on simulations does not provide real-time information on the pollution evolution.

The proposed solution is based on processing real-time data concerning the wave elevation and propagation. To this aim, surface buoys equipped with altimeters are used to get timely measurements of the sea state, [1]-[5].

Directional wave model can be used to predict the wave propagation direction. Different models and procedures have been proposed in literature, [6]-[10]. Nevertheless, several aspects concerning the interpretation and processing of data need to be carefully investigated. Wave propagation direction is today studied for several applications, such as the estimation of sediment transport, the response of coastal structures, or the prediction of the evolution of coastal erosion [11], [12]. Buoy data is processed to get information about the spectrum peak direction and propagation angle, [13]-[15]. The directional wave spectrum is a valuable method to evaluate the wave movements and the sea state. The analysis of wave directional field data is a complex issue. Often monitoring systems are based on empirical data. As a consequence numerical simulations are performed. The authors propose a buoy network to monitor the sea state in real time. A revised model for directional wave analysis is described in Section 2. Section 3 shows the application of the model to predict the propagation of oily pollutants in sea and ocean. Conclusion are reported in Section 4.

2. DIRECTIONAL WAVE MODEL AND SEA STATE

In literature, several wave elevation models have been defined to evaluate the wave vertical displacement. In this paper, surface buoys are used in order to collect a time series of the vertical displacement of the wave free surface referred to the undisturbed average level. A buoy network can be used to get relevant information on the near-shore and off-shore sea state. To this aim, let us consider a buoy which mounts on board an altimeter. Let $\eta(t)$ be the wave elevation or wave vertical displacement over time in a fixed point of the sea, see Figure 4 for reference.

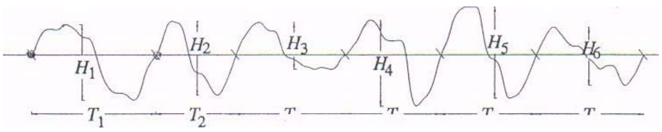

Fig. 4. Wave elevation record over time.

Each elevation value is referred to the average level of sea at rest. It is possible to characterize specific features of a wave. By considering the wave motion in Figure 5, we can define a single wave as the portion of $\eta(t)$ between two consecutive zero up-crossings with the same slope. The time interval between two consecutive zero up-crossings is the wave period.

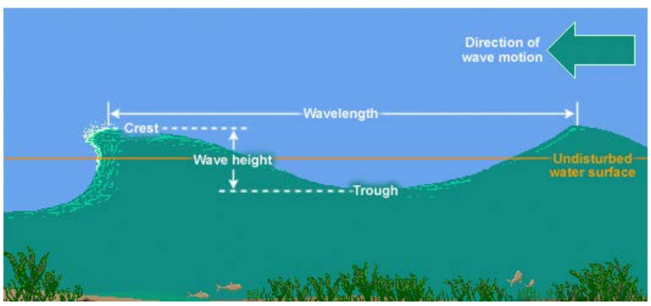

Fig. 5. Wave features.

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The wavelength is the time interval between two consecutive crests, and the crest is the maximum elevation value of a wave. Differently, the trough is the minimum elevation value of a wave. The difference between the elevation values of crest and trough is the wave height.

Suppose to consider a series of wind waves in an undefined time interval with stationary state. Let $\eta(t)$ be a record of N consecutive waves, with N≈100-300. In this assumption, the sea state can be considered stationary and representative of the sea conditions. Assume to consider several records $\eta_i(t)$ of the wave vertical displacement in a specific point of the sea. The time series $\eta_1(t)$, $\eta_2(t)$,..., $\eta_n(t)$ can be considered as a stochastic stationary Gaussian process according to the first-order Stokes theory of sea state. The sea state can be evaluated by the equation:

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

where a_i is the wave amplitude, ω_i the angular frequency and ε_i the phase. The spectrum of the wave elevation $E(\omega)$ is obtained by:

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

where it is $\omega - \delta\omega/2 < \omega_i < \omega + \delta\omega/2$, [16], [17].

The intensity of the sea movement can be evaluated by estimating the standard deviation of the sea state:

$$\sigma = \sqrt{\frac{\eta_1^2 + \eta_2^2 + ... + \eta_n^2}{n}} \tag{3}$$

The significant wave height H_s provides information on the intensity of the vertical displacement:

$$\text{Hs} = 4\sigma \tag{4}$$

The Fourier series $\eta_F(t)$ of the wave elevation is obtained by the expression:

$$\eta_F(t) = \sum_{i=1}^{N} a'_i \cos(\omega_i t) + a_i'' \sin(\omega_i t) \tag{5}$$

where

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

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

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

The line spectrum $E_F(\omega)$ of the wave elevation can be evaluated by:

$$E_F(\omega) = \sum_{i=1}^{N} \frac{1}{2} a_i^2 \delta(\omega - \omega_i) \tag{6}$$

In order to estimate the directional wave spectrum and subsequently the wave propagation direction, let us consider three buoys or measurements points A, B and C like in Figure 6, [18]. The wave elevation in the three points can be estimated by the following equations:

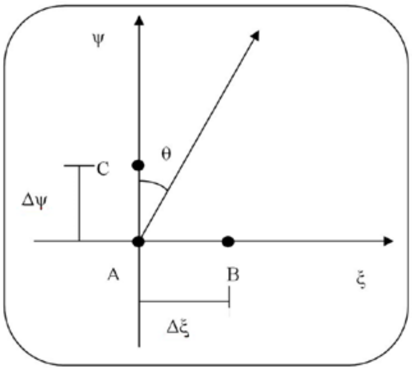

Fig. 6. Wave propagation direction.

$$\eta_A(t) = \sum_{i=1}^{N} a_i \cos(-\omega_i t + \varepsilon_i) \tag{7}$$

$$\eta_B(t) = \sum_{i=1}^{N} a_i \cos(k_i \Delta x \sin\theta_i - \omega_i t + \varepsilon_i) \tag{8}$$

$$\eta_C(t) = \sum_{i=1}^{N} a_i \cos(k_i \Delta y \cos\theta_i - \omega_i t + \varepsilon_i) \tag{9}$$

where k is the number of waves, and θ_i is the angle of the wave prorogation direction. We can rewrite the previous equations as:

$$\eta_A(t) = \sum_{i=1}^{N} A_i^{'} \cos\omega_i t + A_i^{''} \sin\omega_i t \tag{10}$$

$$\eta_B(t) = \sum_{i=1}^{N} B_i^{'} \cos\omega_i t + B_i^{''} \sin\omega_i t \tag{11}$$

$$\eta_C(t) = \sum_{i=1}^{N} C_i^{'} \cos\omega_i t + C_i^{''} \sin\omega_i t \tag{12}$$

Consequently, we can calculate the angle of the wave prorogation direction θ_i by [18]:

$$\theta_i = \arcsin \frac{\arctan \frac{A_i^{'} B_i^{''} - A_i^{''} B_i^{'}}{A_i^{'} B_i^{'} + A_i^{''} B_i^{''}}}{k_i \Delta x} \tag{13}$$

or

$$\theta_i = \arccos \frac{\arctan \frac{A_i^{'} C_i^{''} - A_i^{''} C_i^{'}}{A_i^{'} C_i^{'} + A_i^{''} C_i^{''}}}{k_i \Delta y} \tag{14}$$

In order to consider the effect of the uncertainty in the angle measurement, the combined measurement uncertainty $u_c(\theta_i)$ have been evaluated according to the *Guide to the expression of Uncertainty in Measurement* (*GUM*) in [19]-[21]. By supposing that all input quantities are independent, the combined standard uncertainty is evaluated by the equation:

$$u_c(\theta_i) = \sqrt{\sum_{j=1}^{M} \left(\frac{\partial f}{\partial z_j} \right)^2 u^2(z_j)} \tag{15}$$

where z_j is the generic variable and M is the number of the input quantities. The uncertainty allows us to estimate the direction of the wave propagation by defining the angular interval $\theta_i \pm u_c(\theta_i)$, see Figure 7 for reference.

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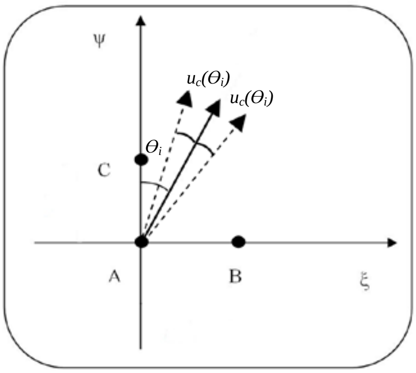

Fig. 7. Revised wave propagation direction.

3. PREDICTION OF POLLUTANT PROPAGATION

The previous model can be used to estimate accurately the wave propagation direction and consequently to predict the propagation direction of the pollutant in sea.

In order to describe the revised model, we have to consider the profile of an oily contaminant fluctuating on the sea. To this aim, as an example, let us consider a detail of Figure 1 shown in Figure 8.

Fig. 8. Contaminant profile.

By considering the wave strength impacting on the contaminant, the direction of the wave action and the initial profile of the contaminant, it is possible to predict the evolution of the contaminant propagation over time. The profile in Figure 8 is discretised into a finite number *n* of linear segments, [11]. Focusing attention on the *i-th* linear segment s_i, it is possible to predict the movement of the single segment (see Figure 9) and consequently to estimate the profile evolution of the contaminant over time. Information on standard uncertainty of the wave propagation direction allows the model to define a more accurate variation range of the propagation. Simulations have been performed in order to validate the model. Experimentation is in progress, so results will be reported in a next work.

4. CONCLUSION

A revised directional wave spectrum model has been proposed to predict the propagation direction of oily pollutants in sea and ocean.

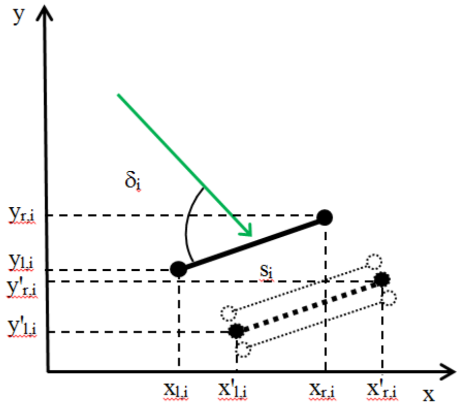

Fig. 9. Evolution of the *i-th* linear segment s_i.

Measurements of wave vertical elevation are carried out by means of surface buoys equipped with altimeters. By the model in [18], the directional wave spectrum is computed. Consequently, the model estimates the wave propagation direction by considering the measurement uncertainty effect. An angular interval provides information on the propagation direction of the contaminant. The present model aims to support the decontamination activities by providing a methodological approach in the delimitation of the intervention area. The advantages of the proposed model are more clear if a contaminant not visible at naked eye is considered. Experimental tests are going to be carried on to validate the model of contamination propagation prediction.

Future work concerns the design of a buoy network with an embedded sensor data fusion algorithm to perform automatically the proposed model. The measurements of altimeters will be synchronized according to the procedure in [22]. Data synchronization will allow us to compensate a misalignment error in the estimation of the contaminant profile evolution.

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