Proceeding Paper

Model for Calculating the Speed of Rip Currents on Open and Sandy Beaches †

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Abstract: A dynamic model is developed to represent rip currents on open and sandy beaches, based on a multiple regression adjustment between the estimated longshore current speed and the rip current speed measured near Duck, North Carolina at the US Army Corps of Engineers Field Research Center. The speed of the longshore current and the tidal current are calculated at incipient breaking and their correlation is established with the speed of the observed rip current, corresponding to the same wave parameters and with the use of the program computer CurveExpert Professional 2.6.3 of the year 2017, a multiple regression equation was obtained to calculate the speed of the rip current, having the best correlation as the independent variable. It was found that larger waves and wave directions closer to the normal to the shore produced stronger rip currents and that strong flows parallel to the shore correspond to lower rip current intensities. The developed model is consistent in calculating the speed of rip currents on open and sandy beaches, with more than 70% accuracy for the locality where instrumental observations are available.

Keywords: longshore current; tidal current; rip current

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1. Introduction

The rip currents appear in the coastal area as compensation for the existence of the dragging of the water mass that accompanies the waves until they break and arrive at the coastal area, where they usually combine with the currents of tide and longshore, generated by the force of the wind; appears a coastal circulation system very dependent on the local geography. On gently sloping beaches with fine sand, where recreational activities are usually carried out, the rip can constitute a serious danger to the safety of bathers. At the international level, the researchs have studied the morphological characteristics, forcing mechanisms and developing dynamic models for forecasting the speed of rip currents, depending on the physical characteristics of each study region. In research by Kumar et al. [1] and Moulton et al. [2], the relationship between the longshore current and the rip current, and its influence on the intensity of the coastal circulation, were studied. Other authors [2–4] included the influence of the tide elevation on the intensity of the rip flow.

The fundamental interest of this research is designing a dynamic model for the numerical prediction of the rip currents speed on open and sandy beaches. Among the relationships studied is the influence exerted by the longshore current and the tidal current on the rip current and the dependence between them.

2. Materials and Methods

2.1. Field Observations

The data of the present work consist of time series of field observations of significant wave height (m), wave direction (°), wave period (s), water depth (m), bathymetry at along the shoreline (m), tidal elevation (m), and rip currents speed (m/s), observed near Duck, North Carolina, at the Field Research Center of the United States Army Corps of Engineers. Currents were observed using bottom-mounted acoustic Doppler velocimeters and profilers on a long, straight beach near Duck for a total of 10 weeks in 2012 and 2013 at 8–15 locations, spanning 100–300 m alongshore and from the shoreline to 3-m depth. [3]

2.2. Development of the Model for Calculating the Rip Currents Speed

Rip currents often appear along the beach, forming circulation cells. Under the influence of the tidal current, they can show a certain periodicity [5]. Longshore currents, parallel to the coast from east to west, when combined with compensation or rip currents, perpendicular to the coast towards the sea, make up the coastal circulation dynamics of the beaches. Tidal currents are incorporated into this dynamic, which in low waters strengthen the component of the coastal current towards the sea. With the real data available in Duck, North Carolina, the longshore current speed was calculated, which is a function of the beach slope, the bottom friction coefficient, the wave height, the depth and direction of the incident wave at the breaking. The tidal current speed at the breaking was calculated.

Subsequently, the correlation between the estimated longshore current speed and the estimated tidal current with the observed rip current speed, corresponding to the same wave parameters, was studied with the help of the CurveExpert Professional 2.6.3 computer program of the year 2017, obtain a multiple regression equation to calculate the speed of the rip current, having as the independent variable the one with the best correlation. A simple analytical solution for calculating the longshore current speed was provided by Longuet-Higgins [6]

$$V_d = \frac{5\pi}{16}\frac{tan\beta^*}{C_f}\gamma_b\sqrt{gd_b}\ sin\alpha_b cos\alpha_b \tag{1}$$

To calculate the height, the direction of the waves and the depth at incipient breaking, the methodology proposed in [7] was used, which takes into account the refraction of the waves in the high seas to the depth of the breaker using the conservation of energy flow, Snell's law and breaker criteria. For the representation of the tidal current speed the approximation of the progressive wave proposed in [8] was used. According to [9] the wavelength (λ) at the total breaking accepted that

$$\frac{h_b}{\lambda} = \frac{1}{7} \tag{2}$$

3. Results and Discussion

3.1. Wave Characteristics at Incipient Breaking

Figure 1 shows the results obtained for the calculation of the wave height, the depth water and the waves direction at the incipient breaking, compared with the values observed in deep waters and the refraction coefficient calculated for each ray of wave according to incidence of the waves, in the experimentation area.

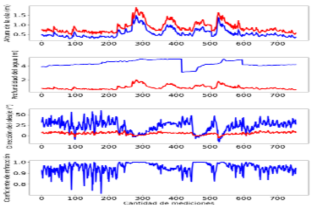

Figure 1. Wave height, depth water, wave direction and refraction coefficient calculated for each measurement. The observed wave elements settled in blue and those calculated at breaking in red.

3.2. Longshore Current Velocity

Longshore current speed depends on the wave height at breaking, the period and angle of incidence of the waves and the slope and roughness of the beach. Figure 2 shows that the highest values of the estimated speeds occur for waves of low height (less than 1m), incident obliquely with respect to the bottom lines, being maximum when the wave approaches 45°. For higher or lower angles, slower currents occur. For all the experiments carried out, the rip current speed in Figure 2 was higher for higher wave heights and wave directions nearly shore-normal, which is consistent with previous field studies and updated salvage statistics by Moulton et al. [4].

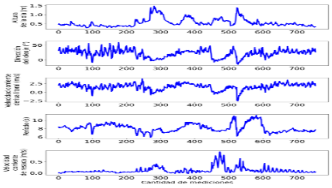

Figure 2. Wave height, wave direction and wave period, observed in deep water, longshore current speed and observed rip current speed.

The observed rip current velocity values showed a relationship and dependence with the wave height and wave direction measurements, with a correlation coefficient of 0.5212 and −0.6021 respectively. Larger waves and wave directions nearly to 0° produced stronger currents. The observed average circulation patterns of rip currents and the longshore currents speed calculated for the corresponding wave parameters in Figure 2, presented a good inverse correlation with a coefficient of −0.5895. Strong flows parallel to the coast correspond to lower intensities of rip currents. This is a result consistent with what was investigated by Moulton et al. [2], that flows produced by obliquely incident waves lead to slower flows directed towards the sea.

3.3. Tidal Current Speed

In numerous studies it has been shown that the tide elevation can influence the intensity of the rip current [3]. In the present investigation, more intense rip speeds corresponded with lower tidal elevations in Figure 3, which corresponds to previous studies by [1]. The strongest rip speeds coincided with higher tidal current speeds. During the high tide or low tide, when the direction of the tidal current coincides with the direction of the rip, the current from the coast to the open sea increases its speed.

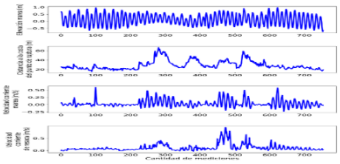

Figure 3. Tidal elevation, distance to shore from at breaking, tidal current speed at breaking, and observed rip current speed.

3.4. Rip Current Speed

The multiple regression analysis that was developed in the CurveExpert Professional 2.6.3 program to obtain a polynomial regressive adjustment between the observed rip speed and the calculated longshore current speed corresponding to the same wave parameters, resulted in that after to compare several models, the most accurate was the polynomial regressive adjustment of degree 20, as it resulted in a correlation coefficient of 0.7049, the highest of all those compared, and the lowest standard error of 0.0995 m/s. The final equation was the polynomial equation of degree 20: $a + bx + cx^2$ …. The partial regression coefficients are shown in Table 1:

Table 1. Partial regression coefficients of the polynomial equation of degree 20.

Coefficient	Numerical Value	Coefficient	Numerical Value
a	0,4422	k	0,5207
b	−0,2317	l	0,5832
c	−1,1134	m	−0,2434
d	1,5177	n	−0,0711
e	2,0495	o	0,0500
f	−3,7486	p	$3{,}8571 \times 10^{-4}$
g	−1,3846	q	$-4{,}7371 \times 10^{-3}$
h	4,0333	r	$6{,}9645 \times 10^{-4}$
i	−0,1020	s	$1{,}4082 \times 10^{-4}$
j	−2,1481	t	$-4{,}5032 \times 10^{-5}$
		u	$3{,}2866 \times 10^{-6}$

Although there is an acceptable adjustment between what is observed and what is modeled, in Figure 4, the model overestimates the rip current speed for longshore current speeds greater than 2.7 m/s, so there is a significant dispersion in these cases and shows a low correlation coefficient of 0.3567. The longshore current usually has values of 0.3 m/s or less and can exceed 1 m/s in special conditions or storms [7]. Isolated values obtained that exceed 2.7 m/s may be the result of errors in data measurements.

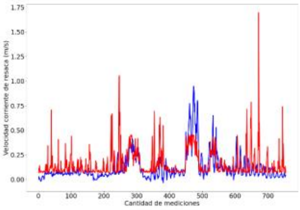

Figure 4. Observed (blue) and modeled (red) rip current velocity.

In the CurveExpert Professional 2.6.3 program, another polynomial regressive adjustment was applied between the observed rip current speeds and the longshore currents speeds, excluding those greater than 2.7 m/s, corresponding to the same wave parameter. The program provided a polynomial regression model of degree 20 whose partial regression coefficients are shown in Table 2.

Table 2. Partial regression coefficients of the polynomial equation of degree 20 for longshore current speeds less than 2.7 m/s.

Coefficient	Numerical Value	Coefficient	Numerical Value
a	0,4358	k	5,2049
b	−0,4155	l	0,0273
c	−0,7689	m	−1,6571
d	3,3376	n	0,3091
e	−0,6572	o	0,2685
f	−8,3565	p	−0,0891
g	5,6811	q	−0,0183
h	8,2032	r	0,0103
i	−8,2626	s	$-1{,}2182 \times 10^{-4}$
j	−3,1148	t	$-4{,}3965 \times 10^{-4}$
		u	$5{,}2267 \times 10^{-5}$

The observed and modeled rip currents velocity is shown in Figure 5. In this case there is a better adjustment and the correlation is stronger with a coefficient of 0.7057 and a standard error of 0.1021 m/s. The correlation was not better because the model underestimated a group of measurements where the observed rip current registered high values, even around 1 m/s.

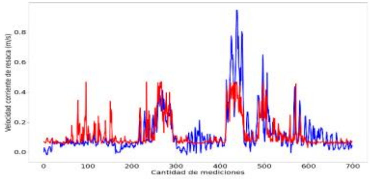

Figure 5. Observed (blue) and modeled (red) rip current speed for longshore current speeds less than 2.7 m/s.

The strong flows measured corresponded to wave directions in deep waters of the northern region very nearly to 0°, whose wave rays suffered very small deviations of less than 1° with respect to the breaking, with refraction coefficients of 0.9999. The results showed that, in general, a wave direction almost perpendicular to the coast is a relevant condition for the generation of rip currents and that the orientation of the coast is, therefore, a fundamental characteristic to consider when evaluating the potential for rip currents on a particular beach.

4. Conclusions

The dynamic model developed with its presented formulation is a consistent tool to calculate the rip currents speed on open and sandy beaches, since the error assessment indicates more than 70% of accuracy for the locality where there are instrumental observations. The speed of rip currents induced by bathymetry is strongly influenced by the wave height, the direction and propagation of the incident waves, the tide elevation and the variations at breaking along the coast, but considering that bathymetry is a conservative property, the variations in the interaction of the waves with the tide are those that decide the magnitude of the rip.

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References

1. Kumar, N.; Voulgaris, G.; Warner, J.C. Implementation and modification of a three-dimensional radiation stress formulation for surf zone and rip-current applications. *Coast. Eng.* **2011**, *58*, 1097–1117
2. Moulton, M.; Elgar, S.; Raubenheimer, B.; Warner, J.C.; Kumar, N. Rip currents and alongshore flows in single channels dredged in the surf zone. *J. Geophys. Res. Ocean.* **2017**, *122*, 3799–3816, doi:10.1002/ 2016JC012222
3. Moulton, M.; Dusek, G.; Elgar, S.; Raubenheimer, B. Comparison of rip current hazard likelihood forecasts with observed rip current speeds. *Weather Forecast.* **2017**, *32*, 1659–1666
4. MacMahan, J.H.; Thornton, E.B.; Stanton, T.P.; Reniers, A.J. RIPEX: Observations of a rip current system. *Mar. Geol.* **2005**, *218*, 113–134
5. Harris, T.F.W. Nearshore Circulations, Field Observations and Experimental Investigations of an Underlying Cause in Wave Tanks. *South Afr. Counc. Sci. Ind. Res.* **1969**.
6. Longuet-Higgins, M.S. Longshore currents generated by obliquely incident sea waves: 1. *J. Geophys. Res.* **1970**, *75*, 6778–6789
7. United States. Coastal engineering manual (CEM). [Washington, D.C.]: [U.S. Army Corps of Engineers]. 2006. Available online: http://app.knovel.com/hotlink/toc/id:kpCEM0000P/coastal-engineering-manual (accessed on).
8. Egorov, N.I. Oceanografía física; MIR, Moscú, Russia, 1983; pp. 553
9. Mitrani, I. *Meteorología Marina*; CITMATEL: La Habana, Cuba, 2017; p. 237