M-SHORECIRC: A Morphodynamic Model

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ABSTRACT


A Quasi-3D morphodynamic model, named M-SHORECIRC, able to simulate the short-term evolution of nearshore sandy regions, is presented. The model is based upon the hydrodynamic model Shorecirc, coupled with a sediment transport module for the estimation of the sediment transport rates, and a sediment conservation equation solver. Presently, it uses the sediment transport equation of Soulsby-Van Rijn, which calculates the total transport for non-cohesive sediments, in combined waves and currents, over horizontal and sloping beds. The present simulations focus on the growth of rhythmic surf zone bottom features, consisting of shoreline-attached normal and oblique bars, and quasi-uniform alongshore bars.

INTRODUCTION

One of the main challenges to the coastal researchers has been to identify, characterize, and represent, accurately, the processes that occur in the nearshore zone. A good understanding of the morphodynamic system is fundamental for the development and choice of more accurate and appropriate coastal models. This is a complex region and research has demonstrated how crucial is to represent correctly the basic hydrodynamic and sediment transport processes embedded in these models.

In the surf zone, observations and models demonstrate that nearshore circulation is complex, even on beaches with relatively simple bathymetry that does not vary substantially along the shore (FALQUÉ et al., 2000; CABALLERIA et al., 2002). Secondly, experimental works within the COAST3D project reveal that even for a straight uniform coast, alongshore current oscillations (shear waves) develop in the intertidal and subtidal zone. The shear waves in the intertidal zone affect both sediment suspension and sediment transport, resulting in migrating 3-D bed-features along the beach. Rather than a stable mean flow, driven only by (breaking) waves and wind, nearshore circulation has been shown in the last decade to include turbulent shear flows and eddies. In addition, the importance of coupling between nearshore waves, currents, and the changing bathymetry is recognized, resulting in the hypothesis that variations in the nearshore bathymetry result from feedback between the driving forces and morphologic changes (SANCHO et al., 2002).

In sandy beaches, outside the surf zone, the transport of sand is friction-dominated; the processes are generally concentrated in a layer close to the seabed and mainly take place as bed load transport in close interaction with small bed forms (ripples) and larger bed structures (dunes, bars). In the surf zone, the transport is generally dominated by the waves through wave breaking and wave-induced currents in alongshore and cross-shore directions. The breaking process as well as the near-bed wave-induced oscillatory water motion can bring relatively large quantities of sand into suspension (stirring) which can be transported as suspended load by net currents such as wave-, tidal, wind-, and density-driven currents (the latter is often negligible compared to the others).

Coastal Models: an Overview

Models of surf zone hydrodynamics can be divided into two categories: short-wave resolving models and short-wave-averaged models. The first, seek to model the entire phase motion of breaking and non-breaking waves. They are based on suitable approximations to the Navier-Stokes equations of motion, keeping the time dependency, which reduce the equations in such a way that they can be solved either analytically or numerically (with a reasonable computational effort).

The second type of models aim to describe mainly the circulation generated by the breaking waves. They do not consider directly the wave motion itself, but only the net effect of the waves over a wave period. Due to this averaging process, the detailed information about the short wave motion is lost, and the net effect of this motion is provided externally, through the so-called “wave driver”, that predicts the forcing for the wave generated currents. Thus, these models gain in simplicity.

Among the wave-averaged models, several approaches have been used. A common approach has been by means of two-dimensional horizontal (2DH) flow models (also known as Coastal Area Models). A second type consists of cross-shore circulation, two-dimensional vertical (2DV) models. Both formulations are simplifications of the three-dimensional problem. A class of models describing a simplified 3D situation, known as Quasi-3D models, have been developed for shallow water flows in estuaries and coastal waters (e.g. DAVIES, 1987; DE VRIEND and STIVE, 1987; SVENDSEN and LORENZ, 1989).

This concept makes use of the existing techniques both for the 2DH and the 2DV (or 1DV) current models and a Quasi-3D models. A class of models describing a simplified 3D situation, known as Quasi-3D models, have been developed for shallow water flows in estuaries and coastal waters (e.g. DAVIES, 1987; DE VRIEND and STIVE, 1987; SVENDSEN and LORENZ, 1989). The concept makes use of the existing techniques both for the 2DH and the 2DV (or 1DV) current models (SANCHO and SVENDSEN, 1997). In DE VRIEND et al., (1995) an overview of coastal area models is available.

The accurate quantification of local sand transport rates in the coastal environment is a condition for the correct prediction of seabed changes and coastline evolution. One of the problems is to know which sand transport formulation should be used. In order to predict the resulting sand transport, many different models have been developed and proposed in the literature. Studies by JANSSEN (1995), BAYRAM et al. (2001), VAN RUN et al. (2001), CAMENEN and LARROUDE (2000), Davies et al. (2002), summarize a wide range of inter-comparisons between sediment transport models. VAN RUN et al. (2003) describe and compare five process-based morphodynamic profile models. These models range from the practical transport formulas, with the sediment transport rate given as a function of the bottom shear stress or the near bottom velocity, to more elaborated models describing in greater detail the bottom boundary layer mechanics. The last can be complex intra-wave mathematical models, involving higher-order turbulence closures, and describe the structure of the flow and sediment concentration near the bottom.

The models based on the assumption that the instantaneous
transport rate is directly related to the instantaneous near-bed oscillatory velocity or bed shear stress, are quasi-steady models (Madsen and Grant, 1976; Bailard, 1981; Soulsby-Van Rijn, 1997; Ribberink, 1998). This implies that these models react immediately to the unsteady oscillatory flow, but do not predict the vertical distribution of velocity and concentration. They are derived either purely empirically, or based on some theoretical or analytical consideration (Janssen, 1995).

M-SHORECIRC MODEL

The primary purpose of the M-Shorecirc model is to simulate and analyze the development and evolution of nearshore bed forms in unconsolidated open coasts in order to understand the responsible mechanisms for the morphologic evolution at small (days)-time scales.

M-Shorecirc is a process-based morphodynamic model and, thus, includes the interaction between hydrodynamic conditions, sediment transport and bed evolution. This means that the hydrodynamics waves and currents adjust to the changing bed morphology, which in turn develops as a function of the hydrodynamic and the sediment fluxes. This model considers the effect of longitudinal and transverse bed slope. For a complete list of the model features, see Table 1.

The morphodynamic model consists of three main modules: the hydrodynamic, the sediment transport, and the morphological module that updates the bottom bathymetry. Each of them is briefly described below.

HYDRODYNAMICAL MODEL: SHORECIRC

The hydrodynamic model includes of a short-wave model, REF/DIF (Kirby and Darlymple, 1994), used as the wave driver. This is coupled with a Quasi-3D nearshore circulation model, forming SHORECIRC (Svendsen et al., 2001; Sanchó, 1997).

The wave driver accounts for combined effects of bottom induced refraction-diffraction, current induced refraction, and wave breaking dissipation. The circulation is forced by the mass and radiation stresses, calculated by the short-wave model.

The theory of SHORECIRC is defined in Putrevu and Svendsen (1999) that is an extension of work of Svendsen and Putrevu (1994) and Svendsen et al. (2001).

The depth-integrated, short-wave-averaged equations can be derived from the Reynolds equations for conservation of mass and momentum. For non-uniform currents over the depth (Van Dongeren et al., 1994; Svendsen and Putrevu, 1994), they are written as:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x} \left( \int_{h_0} V_y u_x dz + Q_{sa} \right) = 0$$

$$\frac{\partial}{\partial t} \left( \int_{h_0} V_y u_x dz + \frac{\partial}{\partial x} \int_{h_0} (u_y V_x + u_s V_y) dz \right) =$$

$$-g \left( h + \zeta \right) \frac{\partial \zeta}{\partial x} - \frac{1}{\rho} \frac{\partial}{\partial x} \left( S_{b0} \int_{-h_0} \tau_{sb} dz \right) - \frac{\tau_{bb}}{\rho}$$

In these equations \( \zeta \) is the surface elevation, \( h_0 \) is the still water depth, \( \rho \) is the fluid density, \( \tau_{sb} \) represents the turbulent shear stress tensor, \( V \) is the horizontal current velocity, and \( Q \) is the depth-integrated volume flux. Furthermore, \( u_s \) is the short-wave velocity component, \( S \) is the radiation stress tensor, and the bottom shear stress is represented by \( \tau_{sb} \). The over bar denotes short-wave (time) averaging; \( t \) is time, and the subscripts \( s \) and \( b \) denote the directions in a horizontal Cartesian coordinate system \((x, y)\).

The contribution of vertically varying currents to the 2DH Model, arising from the convective accelerations, is represented in the second and third terms of Equation 2. Details of its evaluation are given in detail by Putrevu and Svendsen (1999).

The equations above further contemplate the nonlinear interactions between waves and currents, and can be used to analyze coastal circulation in a previously defined bathymetry. Some hydrodynamic phenomena, which have been modeled, are surf beat, infragravity waves, shear waves, and rip currents.

SEDIMENT TRANSPORT MODEL

Presently, the M-Shorecirc model calculates the sediment transport as given by Soulsby and Van Rijn, in Soulsby (1997). This formula applies to the total sediment transport in combined waves and currents, on horizontal and sloping beds. The transport rate results from the addition of bed load to suspended load. Transport due to the wave asymmetry and undertow. Sediment transport and bed evolution in time.

Table 1. Scope of M-Shorecirc.

<table>
<thead>
<tr>
<th>Type of Analysis</th>
<th>Quasi-3d phase-averaged hydrodynamic model, coupled with a sediment transport and morphological module for the analysis of the time-varying nearshore morphology.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographical Extent</td>
<td>Nearshore zone, from the shoreline out to a closure depth. Nearly rectilinear coasts and short-scale morphological modeling (&lt;3 km²).</td>
</tr>
<tr>
<td>Timescale</td>
<td>Short-term morphological modeling; from seconds to a few days (&lt;10 days).</td>
</tr>
<tr>
<td>Applicability</td>
<td>Nearshore and surf zone of the open coast.</td>
</tr>
</tbody>
</table>

Table 2. Basic hypotheses of Soulsby-Van Rijn formula.

<table>
<thead>
<tr>
<th>Grain Size</th>
<th>Considers the non-homogeneity of the size of grain.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave Model</td>
<td>Linear, symmetrical waves</td>
</tr>
<tr>
<td>Transport Mode</td>
<td>Bed load and suspended load, includes transport related with waves and currents.</td>
</tr>
</tbody>
</table>
The formula can be applied in a quasi-steady, instant-by-instant, form, over a period of time, so that the net transport is obtained by integration over time.

Transport rate:
\[
q_t = A_f \left[ -\frac{1}{2} \left( \frac{\partial U}{\partial x} \right)_z, \left( \frac{\partial U}{\partial y} \right)_z \right] (1-1.6 \tan \beta)
\]  
(03)

Total load transport:
\[
A_s = A_s + A_b
\]
(04)

Bed load transport:
\[
A_b = 0.0055(d_{90} / h)^{1.2}
\]
(05)

Suspended load transport:
\[
A_s = 0.0125hD_{50}^{-0.6}
\]
(06)

Threshold current velocity \((U_t)\) of motion (Van Rijn 1997):
\[
\frac{\partial h}{\partial t} = -\frac{1}{\lambda} \left( \frac{\partial q_x}{\partial t} + \frac{\partial q_y}{\partial t} \right)
\]  
(09)

where \(z(x, y, t)\) is the bed level; \(z/t\) is the rate of change of bed level; \(\lambda\) is the porosity of bed material. At every morphological time step the sediment transport rates are computed using the corresponding current velocities obtained from the hydrodynamic model. The time integration of the sediment conservation equation leads to the new bed configuration with which a new flow field is calculated. The time-step \(t\) is chosen in a case-to-case basis, satisfying Courant number (numerical) constraints, and avoiding significant bed changes within one time step.

Algorithmic Implementation

The M-Shorecirc solves the governing equations over a rectangular grid, using a finite difference method. Different schemes are applied to different sub-modules. The hydrodynamic part makes use of a 3rd-order (in time) scheme, whereas, at the present stage, the bed-level equation is solved by a low-order (regressive Euler) scheme. Other methods are being tested as well, where numerical instabilities (due to aliasing and nonlinear effects) are a concern.

The model uses boundary conditions at the seaward boundary \((x=0)\) and the shoreline boundary \((x=L_x)\), and at both lateral boundaries \((y=0\) and \(y=L_y)\), where \(L_x\) and \(L_y\) denote domain lengths in the \(x\) and \(y\) directions, respectively.

STUDY OF SURF ZONE INSTABILITIES

This paper focuses on the growth of non-linear, rhythmic, surf zone bottom features (arising as natural morphodynamic instabilities).

Initial Bottom and Hydrodynamic Conditions

In the following, we consider the initial bed profile as given by Caballeria et al. (2002). It represents a rectilinear coastline, with a quasi alongshore-uniform reference beach profile (Figure 1). The beach is not exactly alongshore uniform as a random perturbation (roughness equal to \(1\) cm) is superposed to the alongshore-uniform profile. The profile consists of a linearly varying bottom, nearer the shore, with slope equal to 1:50, which matches a seaward horizontal bottom \((h=3.4\) m) through a second-order polynomial. This is given by:

\[
h (x) = \begin{cases} 
  h_b + \frac{\beta}{2} (x-x_i)^2 & 0 \leq x \leq x_i \\
  h'_b - \frac{\beta}{2} (x-x_i)^2 & x_i \leq x \leq x_2 \\
  h'_b & x \leq x_2 
\end{cases}
\]  
(10)

where \(h_b\) is the depth, \(h'_b\) is the minimum depth, \(\beta\) is steepness, and \(x\) is the cross-shore coordinate.

The present computational domain has an extension \(L_x=200\) m in the cross-shore direction, and \(L_y=260\) m along the shore. The domain is divided in equally spaced nodes, corresponding to \(x=y=2.0\) m. At the shoreline, a vertical wall is imposed with depth equal to 0.20 m. This implies that, presently, we do not include a moving shoreline boundary condition. At the offshore boundary, an absorbing-generating boundary condition is considered, allowing (long) waves to enter and exit the domain, freely. As the beach is quasi alongshore-uniform, we specify a condition of periodicity at the lateral (cross-shore) boundaries. At the seaward boundary, an incident short wave with height equal to 0.5 m, and period equal to 0.6 s is imposed. Sediment-related and bottom roughness properties are: sediment density, \(\rho_s=2650\) kg m\(^{-3}\); median grain diameter, \(d_{50}=0.25\) mm; \(d_{90}=0.50\) mm; bed roughness, \(z_{0}=0.006\) m, kinematics viscosity of water, \(\nu=1.36\times10^{-6}\) m\(^2\) s\(^{-1}\).

We further focus on two simulations, the first being a normally incident wave \((\theta=0^\circ)\), and the second case being an obliquely incident wave, with angle equal to \(15^\circ\). These cases...
can be considered to as wave-dominated (CABALLERIA et al., 2002).

In our simulations, a zero-velocity initial condition (cold start), at every grid-point, is assumed. The hydrodynamic module is iterated with the initial bathymetry until a nearly steady-state condition is reached. This step includes computing the wave field, wave radiation stresses and volume fluxes and, hence, obtaining the longshore and cross-shore velocities and mean surface elevation. Since wave-current refraction is not significant in the present simulations, wave-current interaction is not included here. Furthermore, we neglect in the present tests the vertical variation of the horizontal currents. That is, we consider the 2DH hydrodynamic model equations, with an enhanced turbulent mixing in order to simulate shear dispersion.

The morphodynamic model is activated after having reached the quasi-hydrodynamic equilibrium. Cross- and alongshore sediment transport rates are computed, and the bed levels are updated according to the sediment continuity equation.

**Development of Medium-scale Bed Forms**

The Figure 2a shows the results of the morphodynamic simulation under normally-incident waves. The grey-scale patterns represent the difference between the final and initial bathymetries, after 3 hr. The arrows correspond to the depth-averaged currents. The shoreline is at the right and breaking occurs, initially, at x=165 m (the surf zone width equals 35 m).

A quasi-longitudinal bar is seen to grow slightly seaward of the breaking line, caused by convergence of transport fluxes. These are forced by including an averaged undertow in the sediment transport formula, estimated as the wave-induced volume flux, divided by the local depth. As the longitudinal bar grows and the depth reduces, breaking occurs over the bar at the final stages of the simulation. Simultaneously, we observe the growth of cross- and alongshore bed features (bars and troughs), that originate as bed instabilities. The flow is mainly shoreward over the shoals and seaward over the pools (troughs).

Figure 2b shows only the bed-forms that are obtained by subtracting the final bathymetry by the averaged bar-profile. These forms are different in pattern from those predicted by CABALLERIA et al. (2002) for the same situation, but similar to those predicted with a larger wave height (H=1.0 m). The differences between their results and ours are due to differences in the models, and the resulting bed-forms are quite sensitive to them as also been explained by those authors. We note that the shoals are periodic, with an alongshore length scale equal to 24 m, approximately.

A result identical to that in Figure 2b (not shown) was predicted for the same wave condition, but without considering an average undertow in the sediment transport formula. In this situation, since the depth-averaged cross-shore velocity is zero, a longitudinal bar similar does not arise, but bed instabilities result as well.

Figures 2c and 3 show the results of the simulation for obliquely-incident waves (15º at x=0), after 3 hr, including the undertow in the sediment transport formula. The waves come from left to right, and bottom to top, in figure 2c. The first figure represents the difference between the final and initial bathymetries, beneath the instantaneous current velocities, and the second shows a 3D perspective of the final bed configuration. As for the simulation with normal waves, a longitudinal bar growths, caused by the undertow. Concurrently, oblique shoals and pools form, periodically, every 32.5 m in the alongshore direction. The shoals are deflected downdrift relatively to the longshore current, which is maximum shoreward the longitudinal bar. Breaking occurs over and past the bar. Thus, surf zone bed-instabilities appear to be able to induce a maximum longshore velocity between the bar and the shoreline.

All the above features grew spontaneously from an initial planar beach, subject to normal and oblique wave attack. Several issues deserve further attention, such as, the role of: the undertow; the wave conditions; the underlying bed bathymetry (planar, concave, bar-type, etc.); and the model sensitivity to the use of other transport formulae.

**DISCUSSION AND CONCLUSIONS**

We have presented the structure of a new morphodynamic model, for the prediction of bed variations within coastal
regions, forced by surf zone breaking waves. The hydrodynamic model can simulate depth-varying currents, although the present results were obtained with a simpler 2DH version. Nevertheless, our simulations account for an average undertow in a simple manner, in the sediment transport formulae, such that we are able to predict the growth of surf zone longshore bars, as in morphodynamic profile models (2DV). The formation and migration of other bed-forms, such as periodic shoals and pools, has also been predicted, in broad agreement with the results of Caballeria et al. (2002).

The development of the present Quasi-3D model, M-Shorecirce, is continuing. Future works include computing other sediment transport formulae, possibly better suited for surf zone regions, such as those by Bailard (1981), Dibajnia and Watanabe (1992), and Silva et al. (2001). We further aim to test a different numerical method for the sediment continuity equation, develop an adaptive morphological time step, which we expect it will reduce some numerical instabilities. Additionally, it is intended to calibrate the numerical model with field data, and integrate the numerical results with those arising from video imaging. We will keep addressing the physical mechanisms involved in the dynamics of the formation and movement of bars, shoals and sand ridges in the nearshore region.

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LITERATURE CITED
