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NUMERICAL SIMULATION OF BED EVOLUTION DYNAMICS: THE PESCARA HARBOR

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KEY POINTS

- *A two-dimensional phase resolving model is used for the computation of the hydrodynamic field in wave-current interaction in the sea regions opposite to the Pescara harbor*
- *The total sediment transport is given by the contribution of the suspended sediment load, calculated by solving the advection-diffusion equation for the suspended sediment concentration, and of the spatial variation of the bed load transport*
- *The proposed model has been used to simulate the silting phenomenon occurring in the sea region opposite to the Pescara harbor in presence of coastal defense structures*

1 INTRODUCTION

In this paper we propose a model for the simulation of the bed evolution dynamics in coastal regions characterized by articulated morphologies.

An integral form of the fully non-linear Boussinesq equations in contravariant formulation, in which Christoffel symbols are absent, is proposed in order to simulate hydrodynamic fields from deep water up to just seaward of the surf zones. Breaking wave propagation in the surf zone is simulated by integrating the non-linear shallow water equations with a high-order shock-capturing scheme. The near-bed instantaneous flow velocity and the intra-wave hydrodynamic quantities are calculated by the momentum equation integrated over the turbulent boundary layer.

The bed evolution dynamics is calculated starting from the contravariant formulation of the advection-diffusion equation for the suspended sediment concentration in which the advective sediment transport terms are formulated according to a quasi-three dimensional approach and takes into account the contribution given by the spatial variation of the bed load transport.

The ability of the proposed model to represent the sediment transport phenomena in a morphologically articulated coastal region is verified by numerically simulating the long-term bed evolution in the coastal region opposite the Pescara harbor (in Italy) and comparing numerical results with the field data.

2 MATHEMATICAL MODEL

The model for the simulation of the bed evolution dynamics here presented is part of the one-way coupling two-phase flow dynamics representations. The model consists of two parts: a first two-dimensional phase-resolving model that makes it possible to calculate the intra-wave hydrodynamic variables, to consider some of the three-dimensional aspects of the hydrodynamic fields and to simulate the run-up and run-down phenomena in the swash zone; a second model for the sediment transport and bed morphological change simulation in which the advection-diffusion equation for the suspended sediment concentration with a quasi-three dimensional approach is resolved and where the contribution given by the spatial variation of the bed load transport is taken into account.

The governing equations are written in an integral contravariant formulation in order to permit the numerical solution of the above-mentioned equations on generalized curvilinear grids representing the articulated morphology of real coastal regions.

2.1 Hydrodynamic model

The hydrodynamic model is based on the scheme proposed by *Gallerano et al.* (2014) for the solution of the fully non-linear Boussinesq equations (FNBE) in contravariant form. In particular, this hydrodynamic model simulates hydrodynamic fields from deep water up to just seaward of the surf zone. Breaking wave propagation in the surf zone is simulated by integrating the non-linear shallow water equations with a high-order shock-capturing scheme: an exact Riemann solver and a weighted essentially non-oscillatory reconstruction technique are used. In order to take into account the sediment transport in the swash zone a procedure for the simulation of the uprush and backwash dynamics of the wet and dry front is used. The near-bed instantaneous flow velocity, the instantaneous wave boundary layer thickness, the friction velocity and the bed shear stress (which are involved in the sediment particle resuspension and settling processes) are calculated by the momentum equation integrated over the turbulent boundary layer.

2.2 Morphodynamic model

The morphodynamic model is based on the wave-averaged advection-diffusion equation for the suspended sediment concentration in which a Q3D approach is adopted for the advective sediment transport terms.

The integral form of the abovementioned equation in contravariant formulation is

$$\iint_{\Delta A} \frac{\partial \bar{\tilde{C}}\tilde{H}}{\partial t} dA + \int_L \left[\int_0^{\tilde{H}} \tilde{C}(z) \tilde{u}^m(z) dz \right] n_m dL = \int_L K_d \tilde{H} g^{ml} (\bar{\tilde{C}})_{,l} n_m dL - D + P \tag{1}$$

where L is the contour line of ΔA and n_m is the m-th component of the covariant outward normal, K_d is given by the eddy viscosity, $\tilde{H}$ is the wave-averaged total water depth, $\tilde{u}^m(z)$ is the vertical distribution of the contravariant component of the horizontal velocity vector obtained averaging over a wave period the modified instantaneous vertical profile of the contravariant component of the horizontal velocity vector (as calculated by the hydrodynamic model taking into account the high order terms in depth power expansion of the velocity and the correction by *Lynett*, 2006) and $\tilde{C}(z)$ is the vertical distribution of the wave-averaged suspended sediment concentration.

The terms related to the line integral on the left-hand side of eq. (1) are calculated starting from the depth integration of the product of the wave-averaged horizontal velocity vertical distribution and wave-averaged suspended sediment concentration vertical distribution, in order to take into account the sediment transport related to the undertow and the effects produced on the concentration by the eddy viscosity vertical distribution.

The source term D, which represents the sediment deposition rate, and the source term P, which represents the sediment pick-up rate, are defined in the following expressions

$$a)\ \ D = \iint_{\Delta A} w_{sed} \tilde{C}_a dA \quad ; \quad b)\ \ P = \iint_{\Delta A} w_{sed} \tilde{C}_R dA \tag{2}$$

where w_{sed} is the sediment fall velocity, $\tilde{C}_a$ is the actual concentration and $\tilde{C}_R$ is the reference concentration (both the concentration values are evaluated at reference height $a = 2d_{50}$).

The value of $\bar{\tilde{C}}$ is obtained by eq. (1). The integration of the eq. (1) implies the calculation at each time instant of $\tilde{C}_a$ and of $\tilde{C}(z)$.

The value of the actual concentration $\tilde{C}_a$, which appears in eq. (2a), depends on the vertical distribution of the wave-averaged suspended sediment concentration $\tilde{C}(z)$. Under wave-current interaction and non-breaking waves, the suspended sediment concentration is determined by the turbulence due to the wave and current. In the case at weak current, the vertical distribution of the suspended sediment concentration is mainly due to the wave-induced turbulence (which is near-bed confined) and, as a consequence, the abovementioned concentration will be greater in the proximity of the bottom. In the case in which the current-induced turbulence is dominant compared to the wave-induced turbulence, the suspended sediment concentration will have a more uniform distribution over the water column. Under breaking waves, the vertical distribution of the suspended sediment concentration is mainly due to the turbulence induced by wave breaking and, consequently, the abovementioned concentration will be greater in the proximity of the free surface (with respect to non-breaking waves). The $\tilde{C}(z)$ depends on the wave-averaged total eddy viscosity $\tilde{\nu}_t(z)$.

The value of the actual concentration $\tilde{C}_a$ must satisfy, as a lower boundary condition, the vertical steady diffusion equation for the suspended sediment concentration

$$-\tilde{C}(z)w_{sed} = \tilde{\nu}_t(z)\frac{\partial \tilde{C}(z)}{\partial z} \tag{3}$$

and must satisfy, as a lower extreme of integration, the integral

$$\bar{\tilde{C}} = \frac{1}{\tilde{H}}\int_a^{\tilde{H}} \tilde{C}(z)dz \tag{4}$$

The calculation of $\tilde{C}_a$ and $\tilde{C}(z)$ which intervene in the second term on the left-hand side of the eq. (1), is performed by means of an iterative procedure, starting from the values of $\bar{\tilde{C}}$ and $\tilde{\nu}_t(z)$.

The reference concentration $\tilde{C}_R$ is calculated starting from its instantaneous values $C_R(t)$ according to the expression proposed by *Zyserman & Fredsøe* (1994) starting from the instantaneous values of the friction velocity calculated by following the approach proposed by *Fredsøe* (1984).

In order to take into account the contribution to the sediment transport from the swash zone, the net cross-shore sediment transport rate from the swash zone is calculated by the *Larson & Wamsley* (2007) expression. The net cross-shore sediment transport rate from the swash zone acts as a boundary condition in the wave-averaged advection-diffusion equation for the suspended sediment concentration [eq. (1)], in order to take into account the interaction between the swash zone and the inner part of the surf zone.

Once the values of the reference concentration and the actual concentration are known, the difference $(P - D)$ between the sediment pick-up rate and sediment deposition rate is calculated. Such difference is inserted into the following bed morphological change equation

$$\frac{\partial z_f}{\partial t} = \frac{1}{1-p}\left[(P-D) + q^{\,l}_{b,l}\right] \tag{5}$$

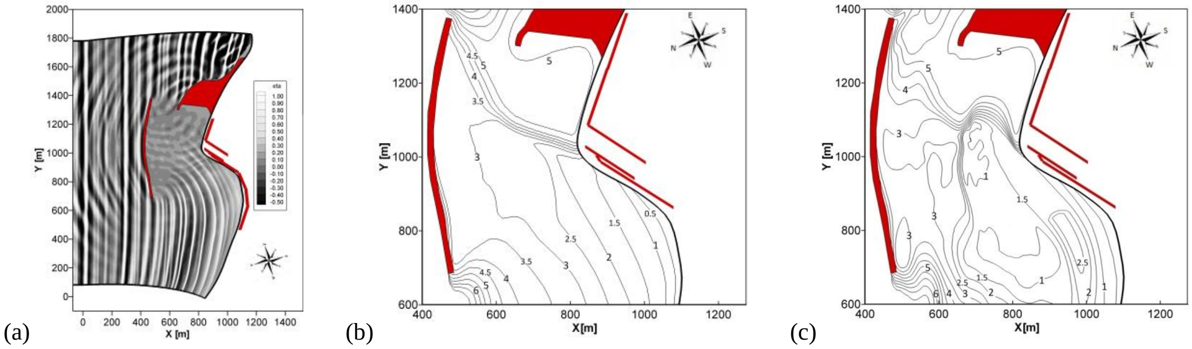
where z_f is the bed elevation, p is the sediment porosity and q_b^l $(l = 1, 2)$ is the contravariant component (in a curvilinear system of coordinates) of the vector $\vec{q}_b$ that represents the bed load transport calculated by means of the *Engelund & Fredsøe* (1976) formula.

The hydrodynamic model and the morphodynamic model are used for the simulation of long-term bed evolution dynamics. The computing of the long-term bed evolution is carried out by a sequence that alternates, at each step (morphological step), the simulation of wave and current velocity fields and the simulation of the sediment transport and bed morphological change.

3 NUMERICAL RESULTS

The capacity of the proposed model to simulate sediment transport processes in morphologically articulated coastal regions, where slightly sloping and regular sea beds alternate with steep irregular bottoms and the coastlines can be characterized by complex shapes or be interrupted by the presence of anthropogenic structures and/or river mouths, is tested by numerically reproducing bed evolution dynamics in the coastal region opposite Pescara river mouth in Italy.

Hereafter the numerical results obtained by means of the proposed model are presented.



(a) (b) (c)

Figure 1. Coastal region opposite Pescara harbor: (a) Instantaneous wave field, (b) Initial depth contour lines for the numerical simulation (c), Calculated depth contour lines at the end of third simulated year.

In Fig. 1(a) an instantaneous wave field, obtained starting from the initial bathymetry and the wave features such as reported in *MIT* 2015, is shown. It can be seen from the figure that wave trains not intercepted by the detached breakwater, first show a steepening of the wave front (shoaling) and then a decay of the wave height due to the wave breaking. In the vicinity of the west and east extremes of the detached breakwater wave fronts undergo a rotation by diffraction.

In Fig. 1(b) the initial configuration of the coastal region opposite Pescara harbor and the related depth contour lines in the outer harbor region are shown (such as reported in *MIT* 2015). From this Figure it turns out that the sea region included between the detached breakwater and entrance of the canal port is affected by silting phenomena. However, in the vicinity of the entrance of the canal port the sharp decrease in the bed levels is due to the dredging operations for the maintenance of navigability conditions.

In Fig. 1(c) the depth contour lines at the end of the third simulated year obtained by means of the proposed model are shown. From the comparison between Fig. 1(c) and In Fig. 1(b), it can be observed a general bed level increment in the sea region included between the detached breakwater and entrance of the canal port; in particular two main accretion areas are observed. The first of the abovementioned areas is located in correspondence of the entrance of the canal port (related to the advancement from south-west to north-east of 1m-to-3m depth contour lines) and the second area is located close to the down drift side of the west extreme of the detached breakwater (highlighted by the emergence of the 3m depth contour line).

The numerical simulation calculates a settled sediment volume in the sea region in question of about 35000m^3/year: this value is of the same order of magnitude as the annual accumulated sediment volume in the three years period 1997-2000 (as estimated from the 1997 and 2000 bathymetric measurement campaigns and such as reported in *MIT* 2015).

The numerical results are in good agreement with the field measurements. Consequently, it can be stated that the littoral sediment transport incoming from north-west is mainly responsible for the silting up in the region included between the detached breakwater and the entrance of the canal port. The numerical simulation satisfactorily reproduces the bed evolution dynamics in the coastal region opposite Pescara harbor.

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