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Soft shore protection methods: The use of advanced numerical models in the evaluation of beach nourishment

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ABSTRACT

Beach nourishment is one of the worldwide most common soft shore protection methods. However, the design of these projects is usually based on empirical equations and rules, leaving large margins of error regarding their expected efficiency. In the present work, an advanced wave and sediment transport numerical model is developed and tested in the evaluation of beach nourishment. Non-linear wave transformation in the surf and swash zone is computed by a non-linear breaking wave model based on the higher order Boussinesq equations, for breaking and non-breaking waves. The new Camenen and Larson (2007), transport rate formula for non-cohesive sediments (involving unsteady aspects of the sand transport phenomenon) is adopted for estimating the sheet flow sediment transport rates, as well as the bed load and suspended load over ripples. Suspended sediment transport rate is incorporated by solving the 2DH depth-integrated transport equation. Model results are compared with experimental data of both profile (cross-shore) and planform morphology evolution; the agreement between the two is considered to be quite satisfactory.

1. Introduction

Beach nourishment comprises the placement of good quality sand on a beach in order to extend the width of a specific coastal stretch or mitigate erosive phenomena; the nourishment location in the cross-shore direction may vary in different beaches from the first dune row to the surf zone depending on the scope of the project (i.e. long- or short-term design), the morphological characteristics and the wave/wind regime of every beach.

The first nourishment project in the US was that of Coney Island, NY, in 1923 (Dornhelm, 1995). The first recorded attempt in Europe was that of Estoril, Portugal, in 1950; a nourishment project in Norderney island, Germany, followed closely after that, with the practice expanding eventually to the rest of Europe until the early '80s (Hamm et al., 2002). On the other hand, it was not until the early '90 s that beach nourishment was introduced as a practice in China (Cai et al., 2011).

Nowadays, periodic nourishment is considered worldwide to be an effective soft-engineering method for both protection and restoration of beaches facing erosive phenomena. According to recent estimates (Hamm et al., 2002) the total annual rate of nourishment in Europe adds up to 28 Mm^3, roughly equal to the respective value for all the Federal projects in the US (i.e. projects with the involvement of the US Army Corps of Engineers). Although similar estimates are not available for China, Cai et al. (2011) attempted a comparison proposing the "volume per unit length" index. The specific index for China (based on data for the main nourishment projects in the country between 1990 and 2009) was found to be less than half of the respective value for European countries, with the projects being smaller in length and total amount of material used, as well.

For a long time the implementation of beach nourishment was essentially based on engineering experience and empirical rules; however, a series of manuals are currently available to support decision-making, design and maintenance in nourishment projects (see Hamm et al., 2002 for a detailed list). Furthermore, and particularly for the design of the beach fill and the evaluation of its performance, the use of numerical models has gradually replaced empirical equations and guidelines. Capobianco et al. (2002) present a detailed description of the model classes, the modelling situations and the elements that are the main sources of uncertainty in nourishment design. The range of the approaches in use varies from shoreline evolution models, to profile evolution models, multi-layer models, and 2D/3D models; exemplary reference can be made to the recent work of van Duin et al. (2004), Larroudé (2008), Shibutani et al. (2009), Kuroiwa et al. (2010), Pan (2011), Van Rijn et al. (2011), Grunnet et al. (2012) and Zhang et al. (2012).

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Models based on the Boussinesq equations have come a long way since the pioneering work of Peregrine in the '60s (Peregrine, 1967), gradually incorporating breaking effects and coupling with sediment transport modules. Zelt (1991) and Karambas and Koutitas (1992) were among the first to incorporate breaking effects using an eddy viscosity analogy, with Kennedy et al. (2000) further improving the representation of wave height decay and setup in the swash. Schäffer et al. (1993) used a different approach based on the Svendsen (1984) roller concept, further improved by Madsen et al. (1997); the specific approach set the basis for the later development of Boussinesq models including vorticity effects as well (Briganti et al., 2004; Musumeci et al., 2005; Veeramony and Svendsen, 2000). Recently, Antuono et al. (2009) proposed an innovative approach on the representation of nonlinear dispersive water waves, and Antuono and Brocchini (2013) a novel approach for the description of wave propagation and flow circulation in the nearshore.

Given that the design of modern nourishment projects should be based on a reliable physical representation of both the hydro- and morpho-dynamic processes in the nearshore and swash, the coupling of Boussinesq models with sediment transport modules emerged as a need in the respective field. The work of Rakha et al. (1997), Karambas and Koutitas (2002), Karambas (2002, 2003, 2012) and Karambas and Karathanassi (2004) confirmed the suitability of the specific approach. The coupled models incorporate nonlinear breaking and non-breaking irregular wave propagation (deep to shallow water and swash), and comprise the prediction of quasi-3D currents and long waves, using the respective information (i.e. breaking wave induced turbulence, near bed velocity asymmetry/acceleration, swash zone dynamics, etc.) to feed complex sediment transport formulae (Wenneker et al., 2011).

In the present work, an advanced phase-resolving nonlinear wave, sediment transport and bed morphology evolution 2DH model (developed by the authors) is tested against profile and planform evolution experimental data for beach nourishment evaluation. Regarding the coastal hydrodynamics, the nonlinear wave transformation in the surf and swash zone is computed by a nonlinear breaking wave model based on the higher order Boussinesq equations for breaking and non-breaking waves. Regarding the bed and suspended sediment load, the transport rate formula proposed by Camenen and Larson (2005, 2007, 2008) is adopted, which comprises unsteady aspects of the sand transport phenomenon (see also the recent formula evaluation by Postacchini et al., 2012). The innovation of this work is the validation of a new Boussinesq-type morphology model, under steep slope conditions and with the presence of a submerged breakwater. The new model is an improved version of the model of Karambas and Koutitas (2002), with the incorporation of a new, well-validated in literature, transport rate formula (after Camenen and Larson, 2007) and a new swash zone transport simulation (after Karambas, 2006). The Camenen and Larson (2007) formula incorporated shear stress directly into bed load transport, as opposed to the Dibajnia and Watanabe (1992) formula used in the original model version of Karambas and Koutitas (2002). Moreover, the suspended load in the formula is related to both wave breaking dissipation and bottom shear stress, as opposed to the model of Karambas and Koutitas (2002), where suspended load was only related to wave breaking dissipation. Applications in the cross-shore direction reproduce experiments presented by Dette et al. (2002) and Di Risio et al. (2010), the later referring to both unprotected and protected nourished profiles by a submerged breakwater. Applications in the planform reproduce experiments presented by Karasu et al. (2008) and Chonwattana et al. (2005).

2. The wave and morphology evolution model

2.1. The phase-resolving wave model based on higher-order Boussinesq-type equations

Models based on the Boussinesq equations have been proven capable of reproducing successfully the phenomena that affect wave-induced morphology of coastal areas. The classical Boussinesq equations have been extended so as to be able to include higher order nonlinear terms, which can describe better the propagation of highly nonlinear waves in the shoaling zone. The linear dispersion characteristics of the equations have been improved as well, in order to describe nonlinear wave propagation from deeper waters (Zou, 1999).

Based on the aforementioned velocity profile, the following higher order Boussinesq-type equations for breaking and non-breaking waves can be derived (Zou, 1999; Karambas and Koutitas, 2002; Karambas and Karathanassi, 2004):

$$\zeta_t + \nabla(h\mathbf{U}) = 0 \tag{1}$$

$$\begin{aligned}\mathbf{U}_t + \frac{1}{h}\nabla\mathbf{M_u} - \frac{1}{h}\mathbf{U}\nabla(\mathbf{U}h) + g\nabla\zeta + G = \frac{1}{2}h\nabla\left[\nabla\times(d\mathbf{U}_t)\right]\\ -\frac{1}{6}h^2\nabla[\nabla\times\mathbf{U}_t] + \frac{1}{30}d^2\nabla\left[\nabla\times(\mathbf{U}_t + g\nabla\zeta)\right]\\ +\frac{1}{30}\nabla\left[\nabla\times\left(d^2\mathbf{U}_t + gd^2\nabla\zeta\right)\right] - d\nabla(\delta\nabla\times\mathbf{U})_t - \frac{\boldsymbol{\tau}_b}{h} + \mathbf{E}\end{aligned} \tag{2}$$

where $\mathbf{M_u}$ is defined as:

$$\mathbf{M_u} = (d+\zeta)\mathbf{u_o^2} + \delta(c^2 - \mathbf{u_o^2}) \tag{3}$$

and G as:

$$G = \frac{1}{3}\nabla\left\{d^2\left[(\nabla\times\mathbf{U})^2 - \mathbf{U}\times\nabla^2\mathbf{U} - \frac{1}{10}\nabla^2(\mathbf{U}\times\mathbf{U})\right]\right\} - \frac{1}{2}\zeta\nabla\left[\nabla\times(d\mathbf{U}_t)\right] \tag{4}$$

In Eqs. (1–4) the subscript t denotes differentiation with respect to time, d is the still water depth, $\mathbf{U}$ is the horizontal velocity vector $\mathbf{U}=(U,V)$ with U and V being the depth-averaged horizontal velocities along the x- and y-directions, respectively, ζ is the surface elevation, h is the total depth ($h=d+\zeta$), g is the gravitational acceleration, $\boldsymbol{\tau}_b=(\tau_{bx}, \tau_{by})$ is the bottom friction term (shear stress components approximated by the use of the quadratic law according to Ribberink (1998)), δ is the roller thickness (determined geometrically according to Schäffer et al. (1993)), $\mathbf{E}$ is the eddy viscosity term (according to Chen et al., 1999), and $\mathbf{u_o}$ is the bottom velocity vector $\mathbf{u_o}=(u_o, v_o)$ with u_o and v_o being the instantaneous bottom velocities along the x- and y-directions, respectively.

The Boussinesq-type equations with the improved nonlinearity and linear dispersion characteristics in deeper water, are accurate to the third order $O(\varepsilon^2, \varepsilon\sigma^2, \sigma^4)$ (Zou, 1999); the nonlinearity and dispersion parameters are defined as $\varepsilon=A/d$ and $\sigma=d/L_0$, respectively, where A=characteristic wave amplitude and L_0=characteristic wave length.

2.2. The sediment transport module

Sediment transport is usually divided into bed load, suspended load and sheet flow. The modeling concepts presently used for the prediction of each one vary, from empirical transport formulas to more sophisticated bottom boundary layer models. In the present work bed load transport (namely q_{sb}) is estimated with a quasi-steady semi-empirical formulation developed by Camenen and Larson (2005, 2007, 2008), for an oscillatory flow combined with a