Modelling the evolution of a Mediterranean beach to optimize nourishment strategies: A numerical approach with a new general sediment transport formula

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Abstract

A modified 2DH morphodynamical model was employed to simulate the evolution of large-scale features with major implications for beach nourishment. A new total load sediment transport formula is first discussed and implemented to better predict the sediment transport in the nearshore, from the offshore to the swash zone. The second part of the study is focused on modelling the evolution of material artificially placed in different parts of the profile, extracting or adding material to the natural bars, and quantifying how the profile responds to different wave climates and nourishment placements. The simulated results were compared with field data from a Mediterranean beach.

Key words

Nourishment, morphodynamical model, sand bar, sediment transport

1. Introduction

In recent years, coastal management has been oriented towards the protection of sandy beaches using different types of artificial nourishment. The overall aim of the present study is to predict the best placement strategy for such sand nourishment depending on the prevailing wave and beach conditions at the site of interest.

Several different working hypotheses concerning the possible use of sand stored in various parts of the profile, for example, sedimentary bars, were investigated. Efforts were made to develop innovative solutions to protect or preserve the littoral environment, simultaneously as unwanted impacts are kept at a minimum. The feasibility of several scenarios was considered, including their respective costs. With regard to the tested scenarios, they should form the basis for developing of a methodology usable by coastal decision makers. The characteristics of the wave climate and its energy were parameterized through a meteorological module in order to facilitate long-term modelling.

One important aspect of morphodynamic models is to accurately estimate the sediment transport in the nearshore region. Many sediment transport formulas have been developed through the years to be applied for the coastal areas (Bayram et al. 2001, Camenen & Larroudé 2002). However, these formulas have typically focused on describing a specific set of physical processes, which limits their applicability for a situation where many processes act simultaneously, for example, around a coastal inlet. Also, many of the formulas have not been sufficiently validated towards data from the laboratory and the field. The first part of this work was made in collaboration with the University of Lund to compare and find a better formula to calculate sediment transport rates.

The morphological evolution of large-scale features in the nearshore region was investigated using a commercial 2DH model and a Multi1DH model (Camenen & Larroudé, 2003b). The simulation of the wave-driven currents was carried out using TELEMAC finite-volume elements. The SISYPHE sand transport module was used to compute sediment transport rates and bed evolution. An undertow model (based on Svendsen approach, 1984) was added, since the sediment transport in the surf zone is mainly controlled by the undertow.

The evolution of beach with different initial placement of the nourishment was simulated over one to several months. Monthly evolutions were studied taking into account the climate event through a meteorological module. This modelling produced good agreement between monthly simulations and field data. Application of the model to the Corniche Beach in France was carried out. This beach is located close to Sète on the Mediterranean Sea having a climate dominated by the wind (Certain, 2002). For the beach, a wave-energy distribution map was developed to determine the appropriate location of the sand nourishment (Larroudé & Camenen, 2004) and comparisons with other nourishments in Mediterranean environment were performed (Boczar-Karakiewicz et al. 2001).

2. Sediment transport

There is a great need in hydrodynamic models for a sediment transport formula that takes into account a wide range of physical factors and conditions. Such a formula should be compared with available measurements from the laboratory and field representing many different situations to ensure robust and reliable behavior. Camenen & Larson (2003) developed a formula that is robust and that yields reliable predictions over a wide range of input conditions. The bed-load transport rate under waves and current was written in the following manner,

$$\Phi_w = a_w \sqrt{q_{cw,on} + q_{cw,off}}\, q_{cw,m} \exp\left(-b \frac{q_{cr}}{\hat{q}_{cw}} \right) \qquad (1)$$

$$\Phi_n = a_n \sqrt{q_{cn}}\, q_{cw,m} \exp\left(-b \frac{q_{cr}}{\hat{q}_{cw}} \right) \qquad (2)$$

where $\Phi = \frac{q_{sb}}{\sqrt{(s-1)gd_{50}}}$ is the non-dimensional bed-load transport, q_{sb} is the bed load transport per unit width, *s* is the sediment density, g the acceleration of the gravity, and d_{50} is the median grain size. The mean and maximum shear stresses $q_{cw,on}$, $q_{cw,off}$, $q_{cw,m}$ are defined as the mean shear stresses over each half periods and the mean shear stress in the direction perpendicular to the waves. T_{wc} and T_{wt} are the half periods where the instantaneous velocity $u = U_c \cos j + u_w(t)$ (or instantaneous Shields parameter $q_{cw}(t)$) is onshore (> 0) or offshore (< 0) respectively (cf. Fig.1). The wave and current friction factor f_{cw} is supposed constant and obtained using the Madsen & Grant (1976) formula, that is a linear combination of the f_c and f_w. $q_{cw,m}$ and $\hat{q}_{cw}$ are the absolute mean and maximum shear stresses. As differences have been found between bed-load load transport under steady current and under waves, a coefficient $a_w = 6Y + 6$ with $Y = \frac{q_c}{q_c + q_w}$ and $a_n = 12$ were proposed where q_c and q_w are the current-related and wave-related Shields parameter, respectively. The exponential coefficient corresponds to the critical Shields parameter effect on the sediment transport. The best fit was found with $b = 4.5$. Eqs.1 and 2 would describe sediment transport as a product between a transporting term ($\sqrt{\theta_c}$) and a stirring term ($q_{cw,m}$).

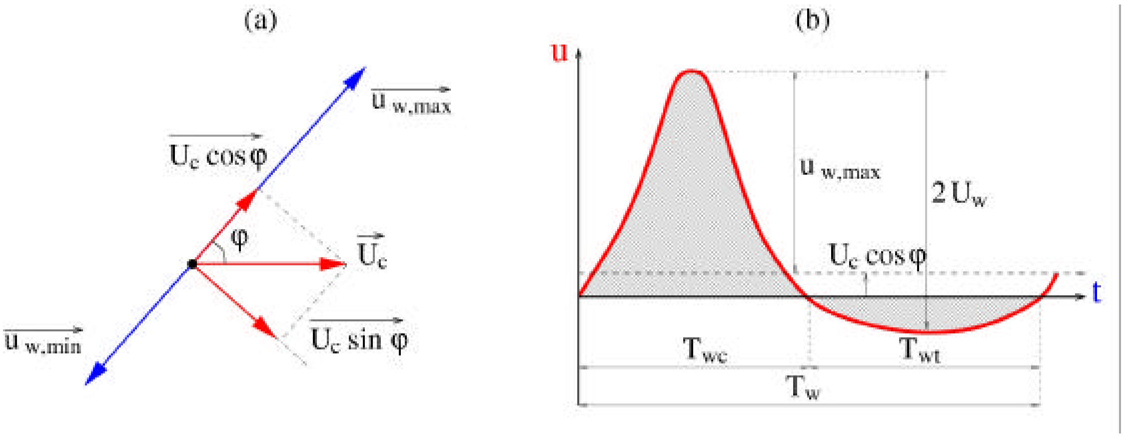

Fig. 1: (a) Notation for wave and current interaction and (b) a typical velocity profile over a wave period in the direction of the waves including the effect of a steady current.

Data on bed-load transport under waves and current are more limited than corresponding data for steady currents. In spite of this, several data sets were compiled from the literature and analyzed for the purpose of comparison with predictions by Eq.1. The data are generally from oscillating wave tunnels experiments (OWT) or oscillatory tray (OT). The calculated and measured bed-load transport for the studied experimental cases was compared and around 60% of the cases are predicted within a factor of two of the measured values. An additional problem when comparing the transport formula with the measurements for the cases including waves is that no shear stresses may be derived from the experiments, but the stresses have to be calculated from estimates of the roughness. This introduces an extra element of uncertainty in the calculations of the transport rates. The formula proposed by Wilson (1987) was employed to calculate the roughness using the skin friction as input.

The suspended load transport (q_s) may be obtained from,

$$q_s = \int_0^h c(z)u(z)dz = U_c \int_0^h c(z)dz \tag{3}$$

where h is water depth, c is the concentration, u the horizontal velocity (varying through the vertical in the general case), z a vertical coordinate, and U_c the mean horizontal velocity. As a first approximation, when determining q_s the vertical variation in u is neglected. Also, to avoid the complication of specifying a reference concentration at a specific level, it was assumed that the concentration profile has an exponential shape, that is, the diffusion coefficient is set to a constant.

Larson and Kraus (2001) studied infilling of navigation channels and employed an exponential concentration profile to estimate the suspended load transport. Wave breaking was assumed to be the main mechanism for the mixing, yielding a concentration profile according to,

$$c(z) = c_R \exp\left(-\frac{W_s}{e} z\right) \tag{4}$$

where c_R is the reference concentration, W_s the settling velocity and e the eddy viscosity. Following Madsen *et al.* (2003), c_R is expressed as,

$$c_R = a \frac{2}{p} \frac{\hat{q}_{cw}}{q_{cr}} \exp\left(-b \frac{q_{cr}}{\hat{q}_{cw}}\right) \tag{5}$$

with $a \approx 610^{-4}$.

In order to employ a general formula for the eddy viscosity it seems natural to assume that,

$$e = k_d \left(\frac{D_c + D_w + D_b}{r} \right)^{1/3} h \qquad (6)$$

where k_d is an empirical constant ($k_d = 0.03$) and D_c, D_w, and D_b are the energy dissipation due to the steady current, the wave stirring, and breaking, respectively. In Eq. 6, the expression for ε produces a constant eddy viscosity over the water depth. The quantities D_c, D_w, and D_b are defined as follows:

$$D_c = 0.5 f_c r U_c^{\ 3} \quad D_w = \frac{2}{3p} f_w r U_w^{\ 3} \quad D_b = rgh \frac{H_w^{\ 3}}{T_w (4h^2 - 2H_w^{\ 2})}$$

Further investigation on the effects of the different types of wave breaking will be carried out, since it may markedly affect the magnitude of the eddy viscosity parameter. The suspended load transport is obtained as before by integrating through the vertical assuming a constant velocity:

$$q_s = U_c \int_0^h c_R \exp\left(-\frac{W_s}{e} z \right) dz \approx U_c c_R \frac{W_s}{e} \qquad (7)$$

In Fig.2 is the bed load, suspended load, and total load plotted together with the wave and current forcing from one of the LSTF experiments (Wang *et al.*, 2002). It appears that the proposed formula quite well described the total sediment transport outside and inside the surf zone. However, the transport in the swash zone was not taken into account properly, so a large underestimation of the sediment transport rate occurs in this zone. As the physics govern sediment transport in the swash zone is quite different, another semi-empirical formula for the transport rate should be employed. Such a formula will make the rate directly affected by the set-up estimation and longshore velocity in the swash zone, producing a second peak in the sediment transport rate distribution as observed by Wang *et al.* (2002).

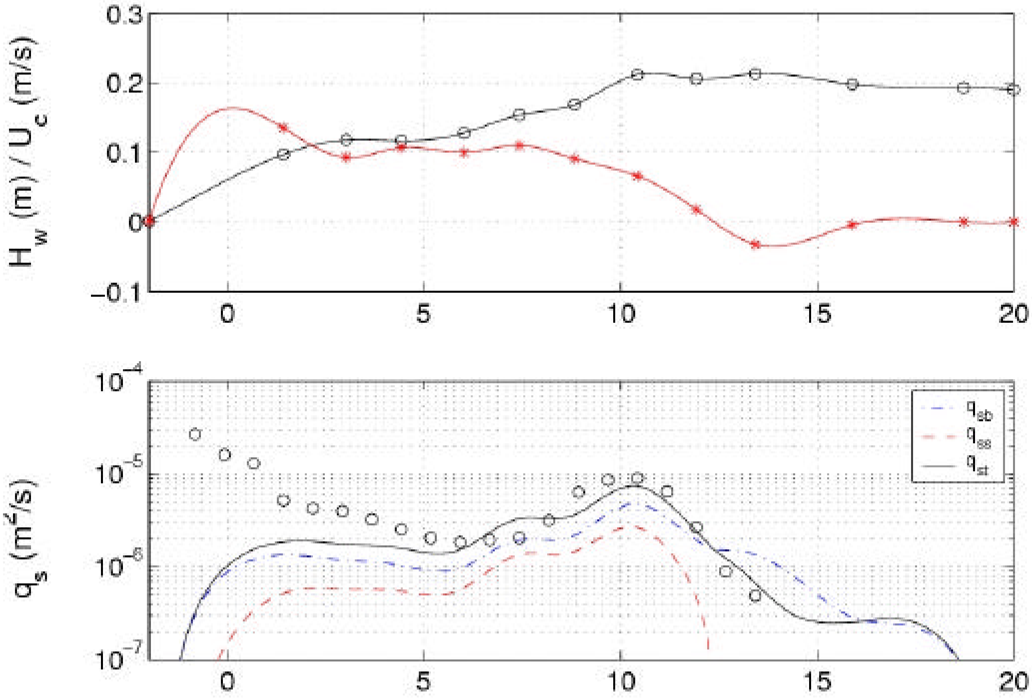

Fig. 2 Comparison between calculated and measured total load transport along a cross-shore profile from the LSTF experiment (data from Wang et al, 2002).

3. Morphodynamic modeling

The primary objective of the present modelling is to describe the morphological evolution in the surf zone and adjacent offshore area. First, simulations were performed on short time scales for different conditions of schematized forcing representing the climatology of the zones of interest (several unit simulations). The performed numerical beach evolution modelling under the action of waves and mean current are based on the coupling of different modules that describe the governing processes at a fundamental level to satisfactorily simulate the sediment movement. Some of main modules of a general type are:

- module that calculates surge including energy dissipation (hyperbolic equation extended by Berkhoff);
- module that calculates mean currents induced by the surge using the concept of radiation constraints obtained from the module of the surge;
- module that calculate sediment transport integrating the combined effects of the surge and the currents induced by the surge (2D or 3D) on the transport.

A model of the morphological evolution in the coastal zone was developed. It is based on a 2DH formulation for the water and sediment motion. The hydrodynamics is decomposed into four systems (waves, littoral drift, undertow, and tidal effects) to compute the evolution of the bottom. Simulation results show a good representation of the wave evolution and the tidal effects on the morphology compared to field measurements (see figure 3).

The TELEMAC software is a general modelling system that employs a finite element method (Telemac Modelling System, 2002). It allows realisation of different hydrodynamic and sedimentary computations including the implementation of the sediment transport formulas.

4. Application to beach protection

The sedimentary offshore bars are more or less rectilinear morphological units, parallel to the shore, where the number of bars typically is a function of the overall beach slope. For the studied beach, one to three bars are present that may potentially be exploited for sand to be used to nourish other parts of the beach.

Several hypotheses for extracting sand from the profile and place it at other locations were tested by means of numerical modelling. The simplest approach involved studying the feasibility of the nourishing the beach by directly extracting sediment from the bars, appropriately selected. It may well be, however, that removing sand from the bars does not involve the desired effects and instead could produce an accelerated erosion of the subaerial portion of the beach. Through a mechanism of action and feedback, the bars take part in the processes of making the waves break, which in turn decreases their potentially erosive effects on the beach. Another hypothesis for nourishing the beach is, thus, to add sediment to the bars themselves to improve their ability to dissipate the incoming wave energy. Questions arise then regarding the source of the material as well as how to determine the most appropriate bar to nourish, and how to do this in the most effective way, possibly using other bars as sources of material for the nourishment.

Thus, a further objective of this study was to carry out numerical modelling of the morphological evolution at the medium term with regard to different beach nourishment strategies. Various scenarios were compared with regard to the simulated sedimentary evolution. The medium-term simulations were based on detailed calculations carried out on short time scales (from one to several days), for various conditions of the hydrodynamic forcing typical of the climatology of the studied area. The short-term calculation results were compiled in a "data base", which was employed in the long-term evaluation of the impact of the nourishment placement. The numerical modelling of the sediment transport and beach evolution under the action of the oblique or frontal swell depends on the coupling of various numerical “tools” focused on the modelling of the fundamental processes related to the movement of the sediment. A sediment transport module integrates the combined action of swell and the currents induced by the swell on the transport of the sediment (see results in figure 3).

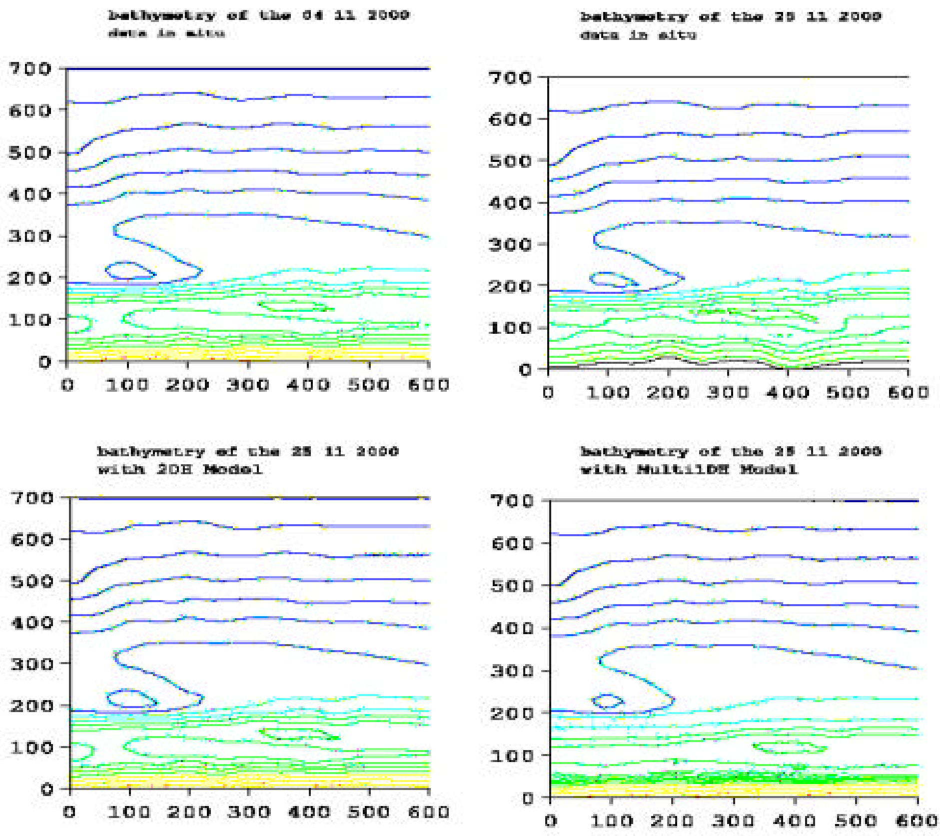

Fig. 3: Results of monthly simulation from the 04 Nov. to the 25 Nov. 2000 on Corniche Beach, France (measurements: a and b; simulated final topography: c the 2dh model and d the multi1dh model).

5. Conclusions

The main result of this study is that numerical results can be compared to an experimental approach. Based on this, it could be easier to determine the time step that will yield the most realistic results. However, some modules, such as the undertow module, may have to be improved, and the interaction between tidal currents and waves should be investigated to compare its effect with the influence of the interaction between the littoral drift and the waves. The approach to decompose the hydrodynamic system into four parts (waves, littoral drift, undertow, and tidal currents) simplifies the numerical computation significantly, but neglects some of the interaction in the system.

During recent years, studies relating to phenomena and processes controlling the transport of sand on coasts produced results that have taken on a fundamental importance in the management of the coastline. These studies have particularly added to the understanding of the following phenomena:

- the formation and evolution of coastal sedimentary bodies (e.g., onshore & offshore bars)
- the relative impact of hydrodynamic processes on sediment transport with regard to representative scales of the beach system, a the interaction between different scales.
- the suitable physical laws to represent the sedimentary fluxes based on in-situ measurements (different transport modes and types of forcing, for example, surge only or the combination waves and current).

The understanding of these processes will improve over time through in-situ measurements, but also by developing mathematical models and numerical codes. An underlying objective of this work has therefore been to model and simulate processes of sediment transport on sandy beaches for varying conditions focused on medium time scales (month). This study was a continuation of previous work carried in the context of development of the software Telemac.

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References

Bayram, A., Larson, M., Miller, H.C., and Kraus, N.C.. Cross-shore distribution of longshore sediment transport: comparison between predictive formulas and field measurements. *Coastal Engineering*, 44, 79-99. 2001

Boczar-Karakiewicz B., Romanczyk W. and Long B., Réhabilitation du littoral par rechargement : Nord-Est de Jerba, Tunisie. In : Proc. Canadian Coast. Conf. Pp 13-25, Québec, Canada. CCSEA, 2001

Camenen B. and Larroudé Ph., Numerical comparison of sediment transport formulae, *Sandwave Dynamics Workshop*, Lille, France, 37-42. 2000.

Camenen B. and Larroudé Ph., Comparison of sediment transport formulae for a coastal environment, *Journal of Coastal Engineering*, 48, pp. 111-132, 2003.

Camenen B. and Larroudé Ph., Un modèle morphologique côtier pour la création de barres rythmiques, *Revue française de génie civil*, in Press, 2003b.

Camenen B. and Larson, M., A bed-load sediment transport formula for the near shore, submitted to *Journal of Coastal Engineering*, 2003.

Certain, R. Morphodynamique d'une côte sableuse microtidale à barres : le golfe du Lion (Languedoc-Roussillon). PhD Thesis, University of Perpignan, 199 pp. 2002

Cheng, N.-S. Exponential formula for bedload transport. *Journal of Hydraulic Engineering*, 128(10), 942-946. 2002.

Larroudé Ph. and Camenen B., 2DH and Multi1DH morphological model for medium term evolution of large scale features and nourishment in the nearshore region: Application to Trucvert and corniche beach (france) and barrosa beach (spain), *Accepted at ICCE*, Lisbonne, 2004.

Larson, M. and Kraus, N.C. Estimation of suspended sediment trapping ratio for channel infilling and bypassing. CHETN-IV-34, U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Miss. 2001.

LNHE-Chatou, Telemac2d - modelisation system of Telemac, version 5.2 – user-validation manual,Technical report, edf-gdf, 2002

Madsen, O.S. Sediment transport on the shelf. Proceedings of the Sediment Transport Workshop DRP TA1, 8-9 June, CERC, Vicksburg, Miss. 1993.

Michel D., Howa H., Thomas C., Chapalain G., Thais L. and Malengros D., Sediment dynamics and hydrodynamics on the inner part of the Aquitan shelf : preliminary results, *Sandwave Dynamics Workshop*, Lille, France, 123-125. 2000.

Meyer-Peter, M. and Müller, R. Formulas for bed-load transport. *Proceedings of the 2nd Meeting of the International Association for Hydraulics Structure Research*, Stockholm, 39-64. 1948.

Svendsen I.A., Mass flux and undertow in the surf zone, *Coastal . Eng.* ,8, 347-365. 1984.

Wang, P., Ebersole, B.A., and Smith, E.R. Longshore sand transport – Initial results from large-scale sediment transport facility. CHETN-II-46, U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Miss. 2002.

Wilson, K. Analysis of bed-load motion at high shear stress. *Journal of Hydraulic Engineering*, 113(1), 97-103. 1987.