



HAL
open science

Numerical Approaches for the Evaluation of Sediment Transport Mechanisms on a Shallow Sloping Sea Bottom

Vasileios Afentoulis, Andreas Papadimitriou, Vasiliki K. Tsoukala, Michel Benoit

► **To cite this version:**

Vasileios Afentoulis, Andreas Papadimitriou, Vasiliki K. Tsoukala, Michel Benoit. Numerical Approaches for the Evaluation of Sediment Transport Mechanisms on a Shallow Sloping Sea Bottom. First International Scientific Conference on Design and Management of Harbor, Coastal and Offshore Works, May 2019, Athens, Greece. hal-02568522

HAL Id: hal-02568522

<https://hal.science/hal-02568522v1>

Submitted on 9 May 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Numerical Approaches for the Evaluation of Sediment Transport Mechanisms on a Shallow Sloping Sea Bottom

V. Afentoulis^{1*}, A. Papadimitriou¹, V. Tsoukala¹, M. Benoit²

¹ Laboratory of Harbour Works, Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, Iroon Polytechniou 5, 15780 Athens, Greece.

² Aix Marseille Univ., CNRS, Centrale Marseille, Institut de Recherche sur les Phénomènes Hors-Equilibre (IRPHE), 49 rue F. Joliot-Curie, 13013 Marseille, France

*Corresponding author: afvas@central.ntua.gr

Abstract

The seabed evolution due to wave–current interaction is examined in the case of a gently sloping bottom in a shallow water coastal area. In this study, an attempt has been made to estimate bed level changes over a time period of 96 hours, under accretive and erosive wave sequences. A numerical model based on the non-linear shallow water equations (NSWE) is utilized in order to simulate the wave propagation and hydrodynamic conditions. Two different approaches are used for the detailed investigation of sediment transport and seabed–fluid interactions. It is shown that the numerical approximation performs reasonably well, as the erosive sequence is characterized by an offshore sediment movement while the sandbar is driven shoreward under accretive wave conditions. The simulation is carried out on a variable coastal bathymetry corresponding to the wave basin experiments of Michallet et al. (2013) at LHF facility (Grenoble INP, France). The obtained results are qualitatively compared with laboratory observations.

Keywords Sediment transport, Numerical simulation, Morphodynamics, Coastal hydrodynamics.

1 INTRODUCTION

The evolution of seabed under the combined action of waves and currents has been extensively studied, but until nowadays is still not fully understood. Historically, many studies have been carried out on the sediment transport pathway investigation, generation and migration of different bed forms, such as ripples and dunes (Sleath 1984), (Nielsen 1992), (Fredsoe and Deigaard 1992), (Soulsby 1997), and (Van Rijn 1993, 2007). Due to the complex nature of these phenomena, it is difficult to strictly interpret their mechanisms with a rational theory. Sand fluxes can be generated and driven by the combination of steady flows (currents) and oscillatory flows (waves). However, several other processes need to be taken into consideration, such as the mean water level variations (tide, wave set-up and set-down), breaking effects, and influence of the bed slope and form (Camenen and Larroude 2003).

The main objective of the present study is to provide a comprehensive understanding of seabed–fluid interactions, using numerical modeling approaches. Hence, a numerical model is employed to simulate the hydrodynamic conditions and morphological seabed changes under erosive and accretive wave sequences. In order to assess the interaction between hydrodynamic and morphodynamic processes, the wave–current–bed evolution system is evaluated in an interactive mode, by considering the feedback on the former from the latter (Wang et al. 2012). Thus, a significant difference of the initial wave height distribution is observed due to the bathymetry changes, while topographically controlled currents are generated as a result of this interaction. It is worth pointing out that the effects of swash and groundwater dynamics in the unsaturated zone of beach is beyond the scope of the present work. Furthermore, measurements and observations from laboratory experiments have been used in order to verify the accuracy and credibility of the numerical approach.

1.1 General model setup

The simulation is carried out on a variable coastal bathymetry corresponding to the wave basin experiments of Michallet et al. (2013) at LHF facility (Grenoble INP, France). Figure 1 depicts the 3D bottom topography colored map and the alongshore-averaged beach profiles at the three main stages of

the experiments. The applied initial wave climates, defined by their significant wave height and peak period, are divided into two main categories: energetic conditions (A: $H_{m0} = 23$ cm / $T_p = 2.3$ s) and moderate conditions with a large period (B: $H_{m0} = 18$ cm / $T_p = 3.5$ s). These wave characteristics correspond to the so-called down-state and up-state wave transitions respectively (i.e. the change from high to low wave energy in the case of the accretive sequence and the change from low to high wave energy in the case of the erosive sequence). The still water depth is set to $h_0 = 0.765$ m and the length and time scales are $1/10$ and $\approx 1/\sqrt{10}$ respectively, using Froude similarity law. Fine sand is considered, with specific gravity (G_s) of 2.65 and a median diameter (d_{50}) of 0.166 mm which corresponds to a settling velocity (w_s) = 2 cm/s. The total simulation time is 96.4 hours and it is divided into two parts, 62 hours duration of B wave conditions and 34.4 hours duration of A wave conditions. In order to create alongshore nonuniformity in the wave breaking spatial pattern, the wave directional spreading at the inlet varies from 20 to 30 degrees.

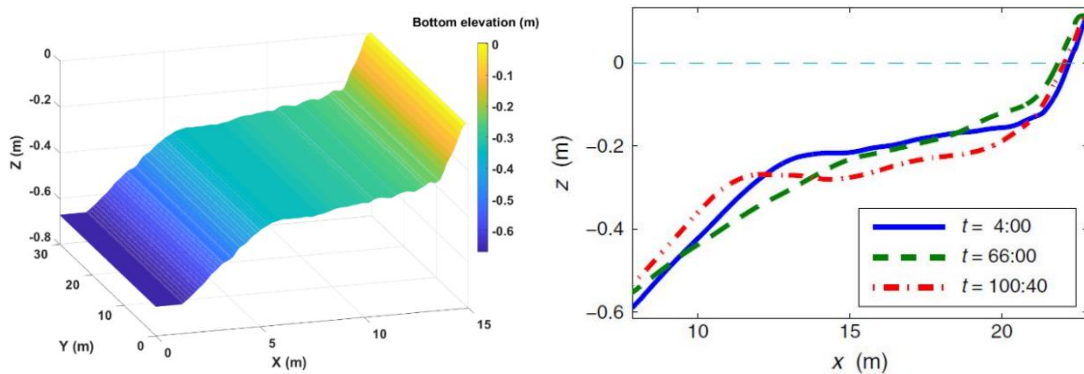


Figure 1. 3D bathymetry colored elevation map (left). Alongshore-averaged beach profiles at the three main stages of the experiments (Michallet et al. 2013) (right).

2 HYDRODYNAMICS

For the assessment of hydrodynamic conditions, a model that solves the two-dimensional non-linear shallow water equations (NSWE) in conservative form is applied (Marche and Bonneton 2006), (Marche et al. 2007). These equations are discretized by a finite volume formulation, which preserves steady state solutions on non-flat sea beds in the absence of perturbations. The main advantage of this numerical approach is that breaking events can be modeled as the development of a free-surface and current discontinuity (Bonneton et al. 2010). It is noted, however, that dispersion effects are not considered, which is a limitation of this approach. A wave-maker is implemented for the generation of irregular waves using directional spectral data. These irregular waves are obtained by superposing a series of wave components with different frequencies and directions, using random phases. In Figure 2 the evolution of wave height distribution during the erosive sequence is shown. The change of the computed significant wave height is due to the wave-bed evolution joint actions.

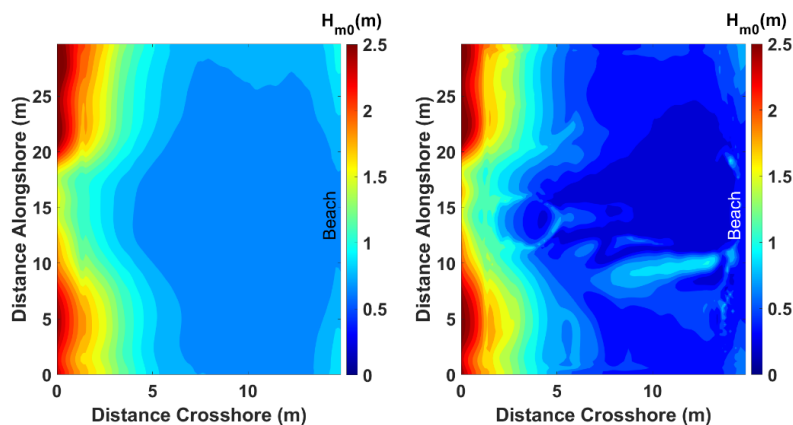


Figure 2. Map of computed significant wave height at the beginning (left) and at the end (right) of the erosive sequence.

3 MORPHODYNAMICS

In the present work, the mode of sediment movement is investigated using two different transport approaches. The first one is based on a quasi-steady approximation suggested by Ribberink (1998) for the estimation of bed load transport, while the suspended transport is calculated from Camenen and Larson's (2005, 2007, 2008) formula. The second approach is based on Soulsby-Van Rijn approximation (Soulsby 1997). This formula applies to total (bed and suspended load) sediment transport in combined waves and currents on sloping beds. Averaged sediment fluxes are obtained, by integrating the transport load over 50 wave periods. Furthermore, a slope limiting methodology is applied to control the maximum bottom slope, which is considered equal to the sediment repose angle (≈ 32 deg) (Bailard and Inman 1981).

3.1 Ribberink's and Camenen – Larson's methods

3.1.1 Bed load transport

Ribberink suggested a model of bed load transport where the solid flux is proportional to a function of the difference between the actual time-dependent bed shear stress and the critical bed shear stress. This formula is described by the following expression for the sand transport rate:

$$q_{SB} = m_{Rib} \sqrt{(s-1)gd^3} \left(\left| \overline{\theta(t)} \right| - \theta_{cr} \right)^{n_{Rib}} \frac{\overline{\theta(t)}}{|\overline{\theta(t)}|} \quad (1)$$

where, $\overline{\theta(t)} = 0.5 f_{cw} |u(t)| \overline{u(t)} / [(s-1)gd]$ is the time-dependent Shields parameter with the instantaneous velocity $\overline{u(t)} = \overline{U_c} + u_W(t)$, s the relative density of sediment and f_{cw} the wave – current friction factor. $\langle \rangle$: time-averaged over several wave periods; and $m_{Rib} = 11$, $n_{Rib} = 1.65$: adjusted coefficients.

3.1.2 Suspended load transport

The Camenen and Larson (2005, 2007, 2008) transport rate formula is adopted for estimating suspended load. This formula is described by the following expression for the suspended load transport:

$$q_{SB} = U_c \frac{C_R \varepsilon}{W_s} \left[1 - e^{-\frac{W_s h}{\varepsilon}} \right] \quad (2)$$

where, $C_R = 3.51^{-3} e^{-0.3d_*} \theta_{cw,m} e^{-4.5 \frac{\theta_{cr}}{\theta_{cw}}}$ is the reference concentration at the bottom with $d_* = \sqrt[3]{(s-1)g/v^2 d_{50}}$ the dimensionless grain size, v the kinematic viscosity of water, $\theta_{cw,m}$ and θ_{cw} the mean and maximum Shields parameters due to wave-current interaction and ε the sediment diffusivity.

3.2 Soulsby-Van Rijn's method

Soulsby-Van Rijn's formula (Soulsby, 1997) was derived for total (suspended and bed load) sediment transport in combined wave and currents on horizontal and sloping beds. This approach is described by the following expression for the sand transport rate:

$$q_t = A_s \bar{U} \left[\left(\bar{U}^2 + \frac{0.018}{C_D} U_{RMS}^2 \right)^{\frac{1}{2}} - \bar{U}_{CR} \right]^{2.4} (1 - 1.6 \tan \beta) \quad (3)$$

where, $A_s = A_{SB} + A_{SS}$ with $A_{SB} = \frac{0.005h \left(\frac{d_{50}}{h} \right)^{1.2}}{[(s-1)gd_{50}]^{1.2}}$ and $A_{SS} = \frac{0.012d_{50}d_*^{-0.6}}{[(s-1)gd_{50}]^{1.2}}$. \bar{U} is the depth averaged velocity, U_{RMS} the root-mean-square wave orbital velocity, C_D the drag coefficient due to current alone, \bar{U}_{CR} the threshold current velocity and β the bed slope.

4 RESULTS AND DISCUSSION

The sea bed evolution at the end of the accretive and erosive sequence using Ribberink's and Camenen – Larson's formulas is presented in Figure 3, while the results corresponding to the Soulsby's approximation are depicted in Figure 4. In Figure 5 alongshore-averaged beach profiles are demonstrated, as obtained using the two methods. It is observed that the numerical approximation performs reasonably well, as the erosive sequence is characterized by an offshore sediment movement while the sandbar is driven shoreward under accretive wave conditions. The obtained results show a good agreement between the two different applied methods, as the identified accretive and erosion areas in Figure 3 and in Figure 4 look similar. However, small discrepancies around the offshore zone are noticed during the accretion sequence. The intensity and direction of the wave-induced currents are determinant for the morphological changes of the sea bottom. The flow is characterized by a rip current, which has a shore-normal orientation and a magnitude of about 0.05 m/s and 0.1 m/s during the accretion and erosive sequence respectively. The intensity of the seaward current causes an offshore sandbar migration under energetic wave conditions. The mean circulations obtained during the experiments of Michallet et al. (2013) have a same mean flow magnitude but their directions are highly variable during each sequence. This is to some extent due to the imposed wave conditions of the experiment, where the wavemaker is designed to have a varying damping at the center of the wave front. Thus, the seabed alongshore nonuniformity obtained by the numerical simulation is more intense. Seabed changes at the end of each numerical simulation (Figure 5) are in the same order of magnitude with the measured ones (Figure 3), between -0.1 m and +0.1 m. Overall, a good agreement between both experimental and numerical results is achieved, as the seabed adapts correctly to the wave climate changes. Further numerical investigations are needed to investigate the transition from the dissipative to the reflective beach state and back again, considering the intermediate sub-states according to the work of Wright and Short (1984).

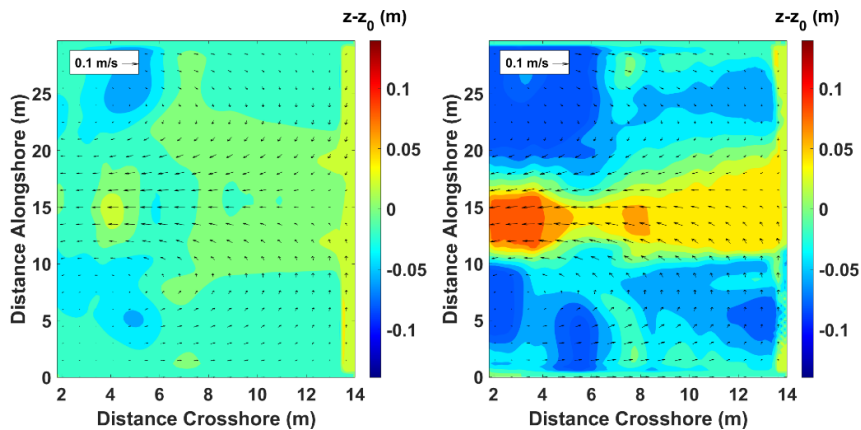


Figure 3 Map of bottom changes and associated mean flow field (vectors) at the end of the accretive (left) and at the end of the erosive sequence (right) using Ribberink's and Camenen – Larson's formulas.

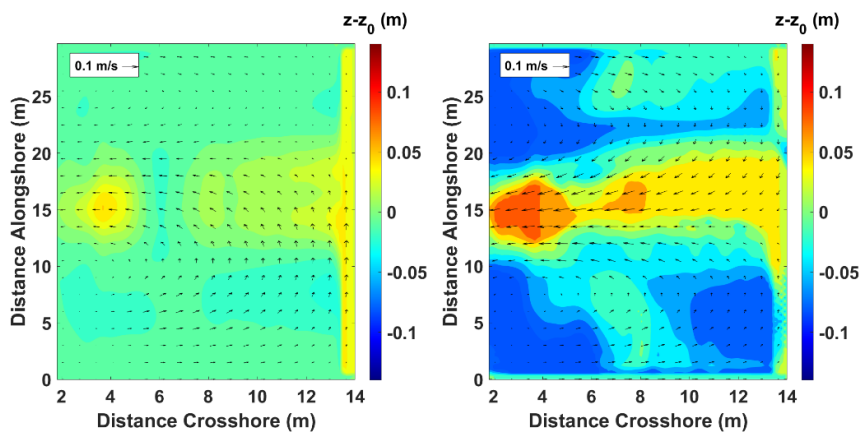


Figure 4 Map of bottom changes and associated mean flow field (vectors) at the end of the accretive (left) and at the end of the erosive sequence (right) using Soulsby's formula.

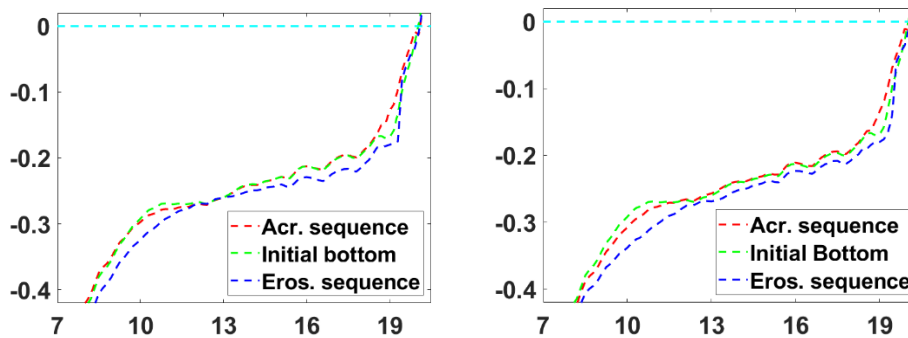


Figure 5 Alongshore-averaged beach profiles at the two main stages of the simulation using Soulsby's formula (left) and Ribberink's and Camenen – Larson's formulas (right).

5 REFERENCES

- Bailard JA, Inman DL (1981) An energetics bedload model for a plane sloping beach: local transport. *Journal of Geophysical Research Atmospheres* 86(C3) : 2035-2043. doi : 10.1029/JC086iC03p02035
- Bonneton P, Bruneau N, Castelle B, Marche F (2010) Large-scale vorticity generation due to dissipating waves in the surf zone. *Discrete and Continuous Dynamical Systems - Series B* 13(4):729-738. doi:10.3934/dcdsb.2010.13.729
- Camenen B, Larroude P (2003) Comparison of sediment transport formulae for the coastal environment. *Coastal Engineering* 48(2): 111-132. doi:10.1016/S0378-3839(03)00002-4
- Camenen B, Larson M. (2005) A general formula for non-cohesive bed load sediment transport. *Estuarine, Coastal and Shelf Science* 63(1-2): 249-260. doi:10.1016/j.ecss.2004.10.019
- Camenen B, Larson M (2007). A unified sediment transport formulation for coastal inlet application. Technical report ERDC/CHL CR-07-1. US Army Engineer Research and Development Center. Vicksburg, MS
- Camenen B, Larson M (2008) A general formula for noncohesive suspended sediment transport. *Journal of Coastal Research* 24(3): 615-627. doi: 10.2112/06-0694.1
- Fredsøe J, Deigaard R (1992) *Mechanics of coastal sediment transport*. World Scientific, Singapore
- Marche F, Bonneton P (2007) A simple and efficient well-balanced model for 2DH bore propagation and run-up over a sloping beach. Paper presented at the 30th International Conference of Coastal Engineering, World Scientific, Singapore
- Marche F, Bonneton P, Fabrie P, Seguin N (2007) Evaluation of well-balanced bore-capturing schemes for 2D wetting and drying processes. *International Journal for Numerical Methods in Fluids* 53(5): 867-894. doi:10.1002/fld.1311
- Michallet H, Castelle B, Barthélemy E, Berni C, Bonneton P (2013) Physical modeling of three-dimensional intermediate beach morphodynamics. *J. Geophys. Res. Earth Surf.* 118(2): 1045–1059. doi:10.1002/jgrf.20078
- Nielsen P (1992) *Coastal bottom boundary layers and sediment transport*. World Scientific, Singapore
- Ribberink JS (1998) Bed-load transport for steady flows and unsteady oscillatory flows. *Coastal Engineering* 34(1-2): 59-82. doi: 10.1016/S0378-3839(98)00013-1
- Soulsby R (1997) *Dynamics of marine sands: a manual for practical applications*. Thomas Telford, London
- Sleath JFA (1984) *Sea bed mechanics*. Wiley, New York.
- Van Rijn LC (1993). *Principles of sediment transport in rivers, estuaries, and coastal seas*. Aqua Publications, The Netherlands
- Van Rijn LC (2007) *Principles of sediment transport in rivers, estuaries, and coastal seas*. Aqua Publications, The Netherlands
- Wang JY, Tang HS, Fang HW (2013) A fully coupled method for simulation of wave-current-seabed systems. *Communications in Nonlinear Science and Numerical Simulation*, 18(7): 1694-1709
- Wright LD, Short AD (1984) Morphodynamic variability of surf zones and beaches: A synthesis. *Marine Geology* 56(1-4): 93-118. doi: 10.1016/0025-3227(84)90008-2