

SEDIMENT TRANSPORT AT THE BALTIC COAST USING A NON-HYDROSTATIC σ -GRID MODEL

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INTRODUCTION

This paper presents the application of a new three-dimensional non-hydrostatic σ -grid model on coastal sediment transport and morphological development under the effects of wave and current. Altering the initial conditions with coastal structures, harbors or groynes, will affect the sediment balance both locally and further away along the coastline. In this paper, an efficient numerical model is introduced to determine the impact of waves, current and structures on coastal morphology. The model resolves the 3D flow field, the free surface, as well as a movable bed boundary. The sediment transport is described via a mass balance equation that determines the development of the bed elevation.

In order to solve sediment transport-related problems at the coast, physical and numerical models are valuable tools. Locally defined sediment transport problems such as local scour can be determined in detail with a 3D hydrodynamic model coupled with a sediment module as in Baykal et. al. (2015) and Li et. al. (2021). Complex structures such as a jacket structure can be evaluated with a 3D CFD model which includes a surface capturing method (Ahmad et al., 2020). Large-scale real-world cases require a great effort to evaluate and high computational cost. An option to reduce cost is to use a one-phase model. A potential flow solver provides an efficient option to resolve large wave fields as presented by Wang et. al. (2021). In order to describe coastal sediment related problems, the viscous effects cannot be neglected. A 2D shallow water model can be a solution, especially with a non-hydrostatic pressure extension (Wang et al., 2020a, 2020b). For more complex free surface flow, the pressure extension is not sufficient which leads to the need of a model that resolves 3D incompressible Navier-Stokes equations but does not need surface tracking to calculate the free surface, which describes two of the advantages of the model presented herein.

NUMERICAL MODEL

The governing equations are the incompressible Navier-Stokes equations. They are written in conservative form in surface and bed following σ -coordinate (Ma et al., 2016, 2012).

$$\frac{\partial h}{\partial t} = \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} + \frac{\partial \omega}{\partial z} = \mathbf{0}$$

$$\frac{\partial \mathbf{U}}{\partial t} = \frac{\partial \mathbf{F}(\mathbf{U})}{\partial x} + \frac{\partial \mathbf{G}(\mathbf{U})}{\partial y} + \frac{\partial \mathbf{H}(\mathbf{U})}{\partial \sigma} = \mathbf{S}$$

Where ω is the vertical velocity within the free-surface and bed-following σ -coordinate where h is the total water depth which consists of the still water level $d(x,y)$ plus

the free surface elevation $\eta(x,y,t)$ (Li and Fleming, 1997). The pressure terms, both hydrostatic and non-hydrostatic in accordance with gradient splitting \mathcal{S}_p , and the turbulent diffusion terms \mathcal{S}_D are included in the source vector \mathbf{S} . Since the current paper evaluates coastal sediment transport problems, viscous stresses need to be considered. The variables are stored at the cell center except the pressure which is solved at the face. The model distinguishes itself by the use of a Godunov-Type Scheme with a HLL Riemann solver (Harten et al., 1983) in combination with a reconstruction with the 5th-order WENO scheme (Jiang and Shu, 1996). The use of conjugated gradient solvers with a geometric multigrid preconditioner from the hypre solver library and parallelization via MPI ensures efficiency. The wave tank adopts methods for wave generation and absorption with relaxation zones (Jacobsen et al., 2012). Coastal modelling includes wetting and drying processes which are captured by a respective algorithm. The sediment transport module is based on a mass conservation equation, where bedload is represented by an excess shear stress formulation. The bedslope and its influence on the critical shear stress is implemented together with an artificial landslide algorithm and ensures a correct representation of the bed dynamics.

VALIDATION

The wave model is tested against plunging breakers according to the experiment by Ting and Kirby (1994). The experiment features a fifth-order cnoidal wave with a wave period of $T = 5$ s and a wave height of $H = 0.128$ m and a still water depth of 0.4 m that are travelling a slope of 1:35. The results of gauges 2 and 3 are shown in Figure 2 with the comparison to the experiment. In the shoaling process from G1 to G2, the wave crest height increases as expected. The breaking occurs from G2 to G3 since a decrease is noticed in G3.

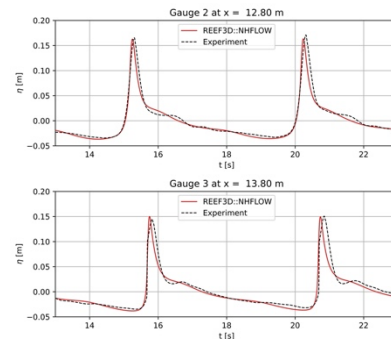


Figure 1 - Modelled and experimental surface elevation of the plunging breaker development at Gauge 2 and 3

REAL-WORLD APPLICATION

The model is applied to a real-world coastal case in Estonia, Pärnu Bay. Valgerand, the beach on the northern coast of Pärnu Bay experiences problems due to longshore sediment transport (Kartau et al., 2011). The beach line retreats as it is facing critical combination of strong storm surges with high water levels in autumn and winter. Groynes are considered a solution. To determine the effect of the groynes and investigate protective options, the area is modelled in an initial scenario. The following wave conditions are applied: JONSWAP spectrum, $H_s=1.4$ m, $T_p = 8$ s (harbour), and 16s with Mitsuyasu type directional spreading (Mitsuyasu et al., 1975) and a factor of 60 for very narrowly spreading sea (beach). The incident waves coming from the gulf approach the Valgerand beach at an inclined angle due to the coastline geometry and bathymetry of the bay, which contribute to the longshore sediment transport under wave actions. The deep channel at the river mouth and the river current split the incoming waves into two sections and contribute to different current circulation patterns and the associated sediment transport and deposition patterns at each side of the river.

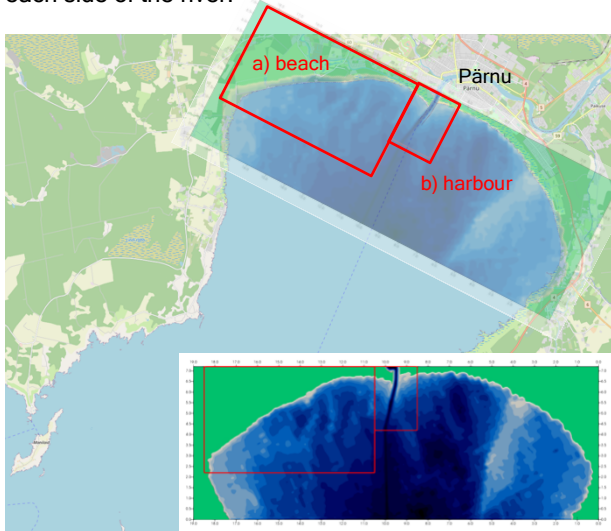


Figure 2 - Overview of Pärnu Bay, Estonia - extract a) the beach (5 x 8 km); extract b) harbour (2 x 3 km)

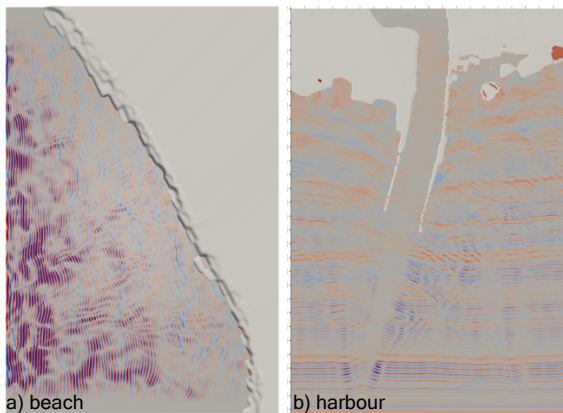


Figure 3 - Estonia Pärnu Bay - model results, free surface, [-0.7, 0.7] m.

CONCLUSION

A new 3D hydrodynamical wave model is presented in this paper. It combines an efficient σ -grid approach with a Godunov-type Scheme and a HLL-Riemann solver for the approximation of the cell face fluxes and a sediment module. The application for a benchmark case with plunging breaking waves shows the valuable shock-capturing properties and delivers promising results in predicting shoaling and breaking processes in an efficient and accurate manner. A real-world application at the Baltic coast shows the capability to represent coastal wave and sediment dynamics in a large-scale case. The model has the potential to offer efficient estimations of the impact of wave conditions in combination with man-made structures on the sediment balance.

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