

# Implementation and validation of an intra-wave sediment transport module in a depth-averaged non-hydrostatic wave model

Anouk de Bakker, Unit of Marine and Coastal Systems, Deltares, Delft, the Netherlands, [anouk.debakker@deltares.nl](mailto:anouk.debakker@deltares.nl)  
Menno de Ridder, Unit of Hydraulic Engineering, Deltares, Delft, the Netherlands, [menno.deridder@deltares.nl](mailto:menno.deridder@deltares.nl)  
Robert McCall, Unit of Marine and Coastal Systems, Deltares, Delft, the Netherlands, [robert.mccall@deltares.nl](mailto:robert.mccall@deltares.nl)

## INTRODUCTION

XBeach (Roelvink et al., 2009) is an open-source numerical model which simulates hydrodynamic and morphodynamic processes and impacts on coasts on the time scale of storms. The original model approach (Surfbeat mode) explicitly solves wave group and long wave (infragravity) dynamics but parameterizes the intra-wave motions of short (sea-swell) waves. On steep beaches and on coastal structures, this parameterization leads to substantial underestimation of wave run-up (e.g., De Beer et al., 2021) and overtopping (Roelvink et al., 2018). Recently, the model was therefore extended with a non-hydrostatic mode that resolves depth-averaged intra-wave motions explicitly (de Ridder et al., 2021). However, this mode did not have a suitable sediment transport module to resolve intra-wave sediment transport and morphological changes.

Several authors already implemented an intra-wave sediment transport formulation in a non-hydrostatic wave model (e.g., Marchesiello et al., 2022;), though the intra-wave transport models with depth-averaged formulations are limited. For example, Rakha et al., (1997) implemented an intra-wave sediment transport model in a Boussinesq model. Furthermore, McCall et al., (2015) implemented formulations for gravel beaches in a non-hydrostatic model. However, the non-hydrostatic depth-averaged XBeach code only contains formulations for suspended transport as derived by Mancini et al., (2021) which was not verified for extreme conditions. Moreover, this implementation is not always consistent with the Surfbeat code.

Here, the Van Rijn (2007) equations for bed load and suspended transport are implemented in a depth-averaged framework for the non-hydrostatic version of XBeach in a similar way as done in the Surfbeat mode. In this abstract the newly implemented sediment transport formulations are presented and validated with large-scale detailed laboratory experiments of dune erosion under extreme storms.

## SEDIMENT TRANSPORT FORMULATIONS

The total sediment transport is represented by a separate bedload transport formulation and a depth-averaged suspended load transport formulation. The bedload transport is given by the formulation of van Rijn (2007),

$$S_{ub} = \text{sign}(\tau_x) \gamma f_{silt} D_{50} D_*^{-0.3} \left( \frac{\tau_x}{\rho} \right)^{0.5} \left( \frac{\tau_x - \tau_{cr}}{\tau_{cr}} \right)^\eta \quad (1)$$

Where  $D_{50}$  is the grain diameter,  $D_*$  is the dimensionless

particle size,  $\tau_x$  is the intra-wave bed shear stress,  $\tau_{cr}$  is the critical bed shear stress,  $\gamma$  is a constant set to 0.5 and  $\eta$  is a constant set to 1. To include bed slope effects the shear stress is corrected using a slope correction.

The evolution of the depth-averaged suspended sediment concentration in time is computed with the advection-diffusion equation. The source term (S) is based on a balance between the upwards motion of sand caused by turbulence and the downwards motion of sand caused by gravity:

$$S = \left( \frac{c_{eq}}{c} - 1 \right) \omega_s c_a \quad (2)$$

Where  $c_{eq}$  is the equilibrium concentration,  $c$  the depth averaged concentration,  $c_a$  the intra-wave reference concentration near the bed and  $\omega_s$  the fall velocity. The equilibrium concentration is given by an integrated Rouse profile with a near bed constant concentration ( $c_a$ ) near the bed, and a Rouse number given by,

$$R = \frac{\omega_s}{\kappa u_*} \quad (3)$$

where  $\omega_s$  is the fall velocity,  $\kappa$  the von Kármán constant and  $u_*$  the intra-wave shear velocity.

The XBeach framework uses a staggered grid with sediment transport fluxes and velocities defined at the cell interfaces and the concentration and water levels located in the cell centers.

## LABORATORY TESTS

To verify the implementation various large-scale dune erosion experiments (Van Gent et al., 2008) conducted in the Delft Hydraulics Deltaflume are modelled and one experiment with a hard structure within the dunes. The hydrodynamic boundary conditions for each test varied between 0.8 to 1.5 m significant wave height, and a peak wave period  $T_p$  of 4.9 to 7.35 s. The diameter ( $D_{50}$ ) of the applied sediment was 200  $\mu\text{m}$ . The duration of the tests was at least 6 h. Detailed measurements in time and space of water pressure, flow velocities and sediment concentrations were performed in the nearshore area.

## RESULTS

To illustrate the accuracy of the model, the hydrodynamic and morphodynamic model predictions for test T01 are shown together with the measured data in Figure 1. Altogether, the short waves (BIAS=-0.015m), infragravity waves (BIAS=-0.06 m) and the setup are accurately modelled. Computed sediment concentrations and the morphological response of the dune and beach are also

well reproduced by the model (Figure 2). The statistical measures for the erosion volume and profile development (between surge level and seaward limit accretion zone with 50% of max accretion) are shown in Table 1 for the three tests.

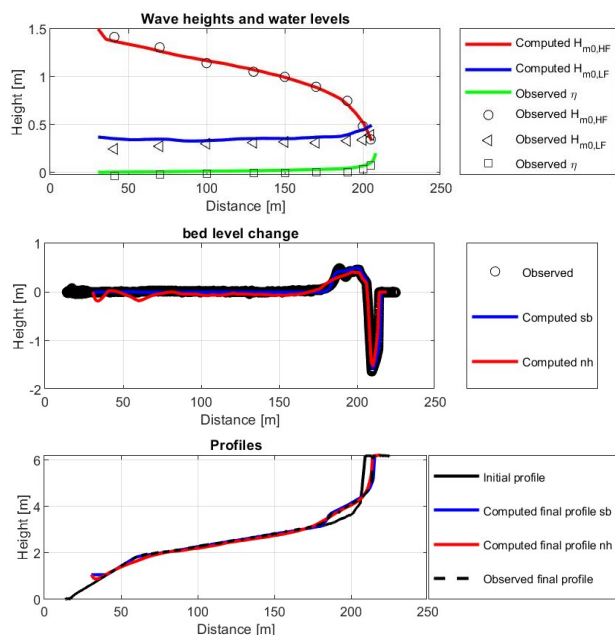


Figure 1 - Modelled predictions compared to measurements for T01. The top panel shows hydrodynamic results, the middle panel shows bed level changes, and bottom panel shows profile development for nonh(nh) and surfbeat (sb).

Table 1 - Overview of predicted results by non-hydrostatic module for Delta Flume experiments.

Test	Erosion volume [m <sup>3</sup> /m]		Bed slope [m/m]	
	Observed	Modelled	Observed	Modelled
T01	8.43	7.8	0.044	0.041
T02	9.25	9.3	0.044	0.039
T03	9.03	8.6	0.046	0.041

Next to the dune erosion experiments, one test with a hard structure is modelled (Figure 2). This test shows the added value of the non-hydrostatic model through short-wave overtopping of the structure, that is not possible with the Surfbeat mode where the incident run-up of short waves is not resolved.

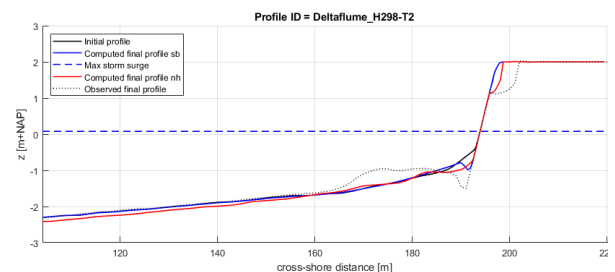


Figure 2 - Model predictions for non-hydrostatic (nh) and surfbeat (sb) mode compared to measurements H298-T2.

## CONCLUSIONS

The Van Rijn (2007) sediment transport formulations have been implemented in an intra-wave framework in the XBeach non-hydrostatic model to simulate estimations of dune erosion during storms. Validation with large-scale flume experiments shows that the model accurately simulates the hydrodynamics and models the morphodynamic behavior reasonably well. This development extends the models' usage for the assessment of hybrid measures and to other types of coasts.

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