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Formation and development of a breaker bar under regular waves. Part 1: Model description and hydrodynamics

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ABSTRACT

In this work a detailed hydrodynamic model is presented, which is used for the study of cross-shore sediment transport and morphodynamics in two dimensions. The model is described in the framework of the generally unstructured, finite volume method. Considerable emphasis is put on those subtleties in the morphological formulation, which are required to achieve mass conservation for the amount of sediment in the bed and in suspension.

In this first part of two, the hydrodynamic description over the cross-shore profile is presented. The model is validated against an experiment with detailed measurements of the free surface and turbulence over a fixed breaker bar profile. A test matrix covering a large interval of the surf similarity parameter is simulated, and the phase lag between the breakpoint and the initiation of the setup is described. The relation of this phase lag to a cross-shore delay in dissipation of organised energy into turbulence is described. The relation of this phase lag to the distribution of the location of maxima in bed shear stresses and magnitude of the undertow is also described. Furthermore, processes in the hydrodynamics, which will have a smoothing effect on the mean cross-shore sediment transport and morphodynamic response are considered.

All simulations are presented for regular waves and for values of the deep-water surf similarity parameter, ζ_0, in the range from 0.08 to 1.19, i.e. covering both spilling and plunging breakers.

1. Introduction

Breaker bars are associated with the process of wave breaking and constitute an important feature in the nearshore morphodynamics; cross-shore as well as longshore. With respect to the cross-shore direction, the bars protect the beaches against erosion by moving the point of breaking further offshore, and with respect to the longshore direction, the breaking on the bars redistribute the radiation field and concentrate the longshore current around the bar. However, this latter may be disrupted by the presence of rip currents.

The behaviour of breaker bars is very dynamic. During storm conditions the bars are moving seaward, while in more calm weather without wave breaking on the bar, the bars have a tendency to move in the shoreward direction accompanied with a decrease in the height of the breaker bar, see e.g. Walstra et al. (2012) for a recent description.

Many field and experimental studies have been performed on the long- and short-term behaviours of the breaker bar (Birkemeier, 1984; Lippmann and Holman, 1990; Ruessink et al., 2000; Wijnberg and Terwindt, 1995), which have shown that the coastal processes are mostly governed by longshore processes on the short term with a shift to cross-shore processes on the longer term. Also, the analysis of decadal field observations of the breaker bar configurations has lead to classification schemes for single (Wright and Short, 1984) and multiple (Short and Aagaard, 1993) breaker bars. The classification is based on Dean's parameter, Ω.

Detailed numerical modelling of the processes has focused on the flow occurring either on a constant slope, or – if the bar is included – on parametric flow descriptions like those by van Rijn et al. (2003), and Ruessink et al. (2007). The hydrodynamic contributions relevant for the cross-shore morphodynamic response are the undertow, Stokes drift, streaming, asymmetry and skewness of the waves (for comparison between some of these contributions see e.g. Fuhrman et al., 2009).

Also three dimensional numerical studies on a constant slope have been done using large eddy simulations (Christensen and Deigaard, 2001) in which the three dimensional vertically descending eddies (Nadaoka et al., 1988) are resolved. These three dimensional features transport sediment from the bottom right to the water surface. Their contribution to the cross-shore sediment transport along with other three dimensional features such as wave spreading cannot be resolved with a two dimensional model as the one presented in this work.

The undertow is one of the main advective agents of the suspended sediment in the surf zone. The undertow is a hydrodynamic response to the depth varying shear stress distribution combined with a perfect balance (in two dimensions) between a net shoreward volume flux above the wave trough and a seaward volume flux below the wave trough (initially discussed by Dyhr-Nielsen and Sørensen, 1970).

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Based on the proposed shear stress distribution by Deigaard and Fredsøe (1989), Deigaard et al. (1991) described the undertow profile using a local fulfilment of the force balance; ignoring any inertial effects. Inertial effects were included in the model by Walstra et al. (2000), who predicted the undertow profiles for the LIP11 experiments (Roelvink and Reniers, 1995) with a parametric and hydrostatic model.

Among the first to attempt the modelling of a breaker bar development was Dally and Dean (1984). They showed how accretive and erosive profiles could be predicted based on the combination of the wave orbital motion, a period average undertow and a prescribed, cross-shore varying, vertical distribution of the suspended sediment transport. This work was followed by Roelvink and Stive (1989), which involved a combination of laboratory experiments and mathematical profile modelling to gain insight into the important contributors to the cross-shore profile development. Based on a Bailard-type energetics sediment transport formulation (e.g. Bailard, 1981), they could turn contributions from e.g. wave asymmetry and undertow on/off through a modification to the second and third velocity moments. By doing so, they showed how the wave asymmetry drives the breaker bar shoreward, whereas the undertow drives it seaward. They also recognised the importance of the phase lag between the point of wave breaking and the initiation of energy dissipation for the correct computation of the undertow.

Where Roelvink and Stive (1989) applied irregular waves, Dally and Dean (1984) used regular waves, and the latter showed to introduce difficulties in the coupling to the morphodynamic response of the breaker bar (related problems are also seen in more recent work by Drønen and Deigaard, 2007; Rakha et al., 1997). They applied either regular incident waves or a regularisation of the incident waves for the computation of the sediment transport, and they produced realistically looking cross-shore profiles. However, the results relied on various types of smoothing of either the sediment transport field or the morphology to avoid unphysically steep slopes on the seaward side of the breaker bar. These slopes originated from the computation of the undertow, which was coupled one-to-one to the wave breaking, such that the undertow disappeared at the point of breaking without any subsequent decay of the inertia. This linked directly to a disappearance of the seaward sediment transport and resulted in large morphological responses. Rakha et al. (1997) also applied irregular waves as a forcing in the same numerical model, and this resulted in much smoother sediment transport fields.

The approaches described above rely on a parameterisation of various relationships across the surf zone, such as the phase lag between the onset of breaking and the initiation of the set-up (Battjes and Janssen, 1978) and the coupling between wave motion and averaged flow features. These parameterisations have previously been derived from laboratory experiments. The last couple of decade work with detailed numerical models (Christensen, 2006; Lemos, 1992; Lin and Liu, 1998) has made it possible to use these detailed numerical models to “measure” the hydrodynamics much more detailed across the surf zone and evaluate quantities, which are difficult to measure. Lately, advances in computational speeds have allowed for simulations, which reach steady state conditions for incident regular waves (Jacobsen et al., 2012) and quasi steady-state conditions for irregular waves (Ruju et al., 2012) have been reached.

1.1. Scope of present work

The scope of the study is to make a detailed description of the 2D breaker bar, including its shape and its crossshore movement. This is done by introducing a thorough numerical description of the waves and the wave induced mean flow, as the waves propagate from outside and through the surf zone. Hereby, wave asymmetry, wave skewness, wave breaking, and phase lag between the maximum wave height and maximum bed shear stresses are all included. Also, the sediment transport is phase resolved, so phases introduced between the hydrodynamic forcing and the suspended sediment transport is accounted for. The numerical model is able to handle an arbitrary bed topography, so the morphological development can be followed, which is done in Part 2 of this study. This real morphodynamic description differs from the earlier work described above by not only “creating a bar” by collecting sand from off- and onshore, but also calculating a (model)-correct profile of the bar including its cross-shore width and height. One example on the usefulness of such a description is given by Jacobsen and Fredsøe (2014a), in which the model has been used to evaluate the destiny of bar-nourished sand.

1.2. Structure of present work

First, an extensive model description of the coupling between the hydrodynamic model and the sediment transport and morphodynamic modules is presented. A special emphasis is put on the handling of the contributing terms to the morphological response on the detailed level of a single computational cell.

Secondly, the hydrodynamic model is tested over fixed bottom profiles with both a constant slope and a barred profile. The results are compared with laboratory and field observations. The objectives of Part 1 of the study are to describe/predict the hydrodynamic processes and phase lags under breaking, regular waves to identify natural smoothing processes, which can generate realistically looking breaker bar profiles without the introduction of any artificial smoothing, see the Introduction section above.

In the accompanying paper (Jacobsen and Fredsøe, 2014b) the sediment transport and the morphological development will be considered both for the validation with a laboratory experiment and in a parametric space to yield quali- and quantitative measures of the sediment and morphodynamics processes over the cross-shore profile. The sediment and morphodynamic processes will be coupled with the phase lags identified for the hydrodynamics to obtain additional knowledge on the important parameters governing the breaker bar development. Also the intra-wave processes in the sediment transport will be considered and related to the intra-wave hydrodynamics.

2. Numerical model

The numerical model is based on the open-source computational toolbox OpenFoam®, v. 1.6-ext, and utilises the possibility of performing parallel computing. OpenFoam is not natively available for sediment transport and morphological computations, thus it has been extended to include these functionalities.

OpenFoam uses the finite volume methodology on a collocated variable arrangement.

2.1. Hydrodynamics

The hydrodynamics rely on a solution to the Reynolds Averaged Navier–Stokes equations (RANS) with a k–ω turbulence closure (see Jacobsen et al., 2012, for details). The Navier–Stokes equations are solved for both the air and the water. The production of turbulence, k, and that of the characteristic turbulent frequency scale, ω, are based on the rotation rather than the strain tensor of the velocity field, $\mathbf{u}$, in order to avoid turbulent production in the potential part of the flow (Mayer and Madsen, 2000). Other hydrodynamic properties are the excess pressure, p^*, the molecular and turbulent viscosities, ν and ν_t, and the density, ρ. The free surface is captured using a volume of fluid (VOF) approach on the variable α, where $\alpha = 1$ for water and $\alpha = 0$ for air; any intermediate value reflects a mixture of the two fluids, though it should be stressed that the underlying assumption of the VOF model is that the two fluids are immiscible. Details specific for this VOF model are found in Berberović et al. (2009).

Waves are generated utilising the “waves2Foam” toolbox by Jacobsen et al. (2012), who have showed that simulation times in excess