7.18 Modelling water motions and bed form dynamics in shallow water

Swart, H.E. de[1], Hulscher, S.J.M.H.[1]

[1] University Utrecht, The Netherlands

* Institute for Marine and Atmospheric Research, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands
** Delft Hydraulics, P.O. Box 152, 8300 AD Emmeloord, The Netherlands

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1. Introduction

In this extended abstract a brief overview is presented of work which has been carried out during the MAST2 period at Utrecht University. Three different topics were investigated, i.e., the behaviour of tidally induced large-scale bed forms in offshore coastal seas, the formation of sand bars on the shoreface and the excitation of edge waves and steady currents in the coastal zone. The results of these different projects will be discussed in the next sections.

2. Tidally induced off-shore bed forms

This project was carried out in order to obtain a better understanding of the behaviour of observed rhythmic bottom patterns, like sand ridges and sand waves, in offshore coastal seas with strong tidal currents. The ridges are quasi-steady features with length scales of order 1-10 km, the crest orientation is slightly anticlockwise with respect to the principal tidal current direction and their amplitudes range between 10-50% of the local water depth. Sand waves seem to be progressive (a few meters per year, although this is subject to discussion), they have shorter wave-lengths (100-700 m) with crests which are almost perpendicular to the major axis of the tide and their amplitudes are usually a few meters.

The objective of the project was to develop an overall model which is able to simulate the evolution of both sand ridges and sand waves. The motivation for this approach was that observations indicate that, depending on the geographical location, there may be either no bed forms or sand ridges, or sand waves or the two types of patterns occur simultaneously.

The state of the art at the beginning of this project was that the formation of sand ridges can be explained with a tidally driven depth-integrated shallow water, supplemented with a bed evolution equation and a simple parameterization of the sediment transport, see Huthnance (1982) and extensions by Hulscher et al. (1993). Moreover there were models of Fredsoe & Deigaard (1992) which explain the characteristics of fully developed sand waves using a quasi-steady model which is not driven by tides.

Based on this knowledge it was realized that in order to model tidally induced sand waves the vertical structure of currents needs to be included. Therefore an extended two-dimensional model was developed in which the veering of horizontal currents in the vertical due to earth rotation effects was included, see De Swart & Hulscher (1995). As a consequence the directions of the net sediment transport and of the principal tidal current will differ, depending on the Ekman number E (which measures internal friction) and a slip parameter s (measures bottom resistance). Moreover, the sentivity of the model results with respect to the incorporation of a critical shear shear stress for erosion, parameters in the transport parameterization, etc., was investigated.

In the study the stability of a basic state, which describes a spatially uniform tide over a flat bottom, with respect to small bed form perturbations of arbitrary scale and orientation is investigated. In case positive growth rates are obtained the basic state is unstable and the perturbation with the largest positive growth rate is called the preferred mode.

In particular for small values of E and moderate values of s it was found that the crests of the most preferred bed forms can have a clockwise orientation with respect to the major tidal axis. This result might be relevant for understanding the presence of shore-face connected ridges which also have such an orientation. However, the extended 2D model does not predict the formation of sand waves.

Therefore, in De Swart & Hulscher (1995) a parameterized three-dimensional model was developed and analyzed which incorporates to some extent the vertical structure of flow perturbations induced by the bed forms. The model concept is useful in case either vertical effects can be neglected (the ridge regime) or if the flow perturbations are confined to a thin boundary layer close to the bottom (the sand wave regime). An important conclusion is that the model predicts both the formation of sand ridges and sand waves, see figure 1. Furthermore, the characteristics of the most preferred bed form appear to depend strongly on the two parameters E and s, mentioned above.

Since the parameterized three-dimensional model is highly idealized and is of limited use to compare with observations, it was decided to develop and study a morphodynamic model based on the full three-dimensional shallow water equations. Since now the full feedback between bottom and currents is described the differential equations which result from the application of the linear stability analysis have to be solved numerically (shooting methods). The basic concepts and results are extensively described in Hulscher (1995).

An important conclusion is that, depending on the values of the Ekman number E and slip parameter s, the model predicts four different types of regimes, see figure 2. For small to moderate E and small s no bed forms are found: all perturbations appear to have negative or zero growth rates. For moderate s and moderate to large values of E the most preferred bed forms resemble characteristics of sand ridges. In the third regime (large values of s and s/E) sand waves are obtained. Finally, for moderate values of the slip parameter and small Ekman numbers bed forms are obtained of which the crests are almost parallel to the principal direction of the bed shear stress vector.

The model has been compared with some observations carried out at various locations in the North Sea and there seems to be satisfactory agreement. However, a serious limitation of all the models discussed so far is that they are only valid for small bed forms since they are based on a linear stability analysis. Hence the models do not yield information on the finite amplitude behaviour and interaction of the various types of bed forms. Extending these models to incorporate nonlinear effects causes serious problems because for realistic parameter settings there is always a wide spectrum of perturbations with positive growth rates. Thus the model is strongly nonlinear and difficult to analyze. Moreover, there is no physically acceptable combination of model parameters for which a narrow spectrum of bed forms can be obtained, which is a necessary condition for the application of a weakly nonlinear analysis. This problem is still under investigation.

3. Sand bars on the shoreface

At present an idealized morphodynamic model of the shoreface is under investigation. The water motions are described by the Boussinesq equations and limited to a first and second harmonic. Using a multiple scale analysis, where it is assumed that bottom variations take place on a spatial scale which is large compared to the wave-length of the first harmonic, equations for the wave amplitudes can be derived. They describe both nonlinear wave-wave interactions, wave-bottom interaction. This results in asymmetric waves, causing net sediment transports and thereby an evolution of the bottom.

In numerical experiments of Boczar Karakiewicz (1988), see also references herein, it was found that the bottom always evolves towards a rhythmic pattern which resembles observed shore-parallel bars. The length scale of the bars is close to the so-called repetition length, the scale on which the first and second harmonic exchange their energy.

The aim of the present study is to give a physical explanation of this phenomenon. To this end the model of Boczar Karakiewicz has been extended with steady currents as well as forcing (due to radiation stresses) and dissipation mechanisms. In case of a flat bottom the model allows for a basic state which describes a cnoidal wave. If small wavy bed form perturbations are introduced the growth rate appears to have a maximum in case the length scale of the perturbations is of the same order as the repetition length, see figure 2. Results strongly depend on the friction coefficient, in case of an ideal fluid an infinite reponse occurs. A further analysis should reveal more about the basic physical mechanims responsible for this behaviour. A paper on this topic is in preparation (Hulscher, 1995) and will be part of a thesis to be presented next year (Hulscher, 1996).

4. Edge waves and steady currents in the coastal zone

This is a joint project with the University of Genoa, see also their abstract. Edge waves and rip currents are believed to be important hydrodynamic agencies for the formation of various types of bed forms in the coastal zone, such as crescentic bars and beach cusps. These features can be generated by several mechanisms, in this project we have focussed on the resonant excitation of edge waves due to an incoming wave approaching a beach in water with variable depth. In previous studies only standing waves were considered, in the present project a model has been developed which accounts for the effects of partial reflection (Blondeaux et al., 1994) or the presence of a vertical cliff at the coast-line (De Swart et al., 1995). In both cases a new class of edge waves has been discovered.

In Blondeaux et al. (1994) the model is applied to the region just outside the surf zone were the effect of wave breaking is included parametrically in the reflection coefficient. It is found that, depending on the geometrical characteristics of the beach, the lowest-order subharmonic standing edge waves are not always most favourable as is found for fully reflective beaches. In general growth rates decrease with decreasing values of the reflection coefficient, thereby suggesting that in case of dissipative beaches other instability mechanisms might be more important.

A different model is discussed in De Swart et al. (1995). Here the coastal boundary is represented by a vertical cliff such that the incoming waves are fully reflected. In this case the growth rates of edge waves strongly depend on the position of the cliff and subharmonic edge waves donot always appear to be the most preferred modes. In this model also the interaction between the incoming wave and synchronous edge waves are investigated. This results in steady responses which, due to the structure of the edge waves, have a pronounced variation in the longshore direction, see figure 3. The corresponding current patterns resemble rip current systems.

At present the stability of the wave set-down, caused by radiation stresses induced by the incoming waves, is investigated. Furthermore, the model will be supplemented with a morphological component, such that sediment transports and bed form changes can be investigated. Two further papers on these topics are in preparation.

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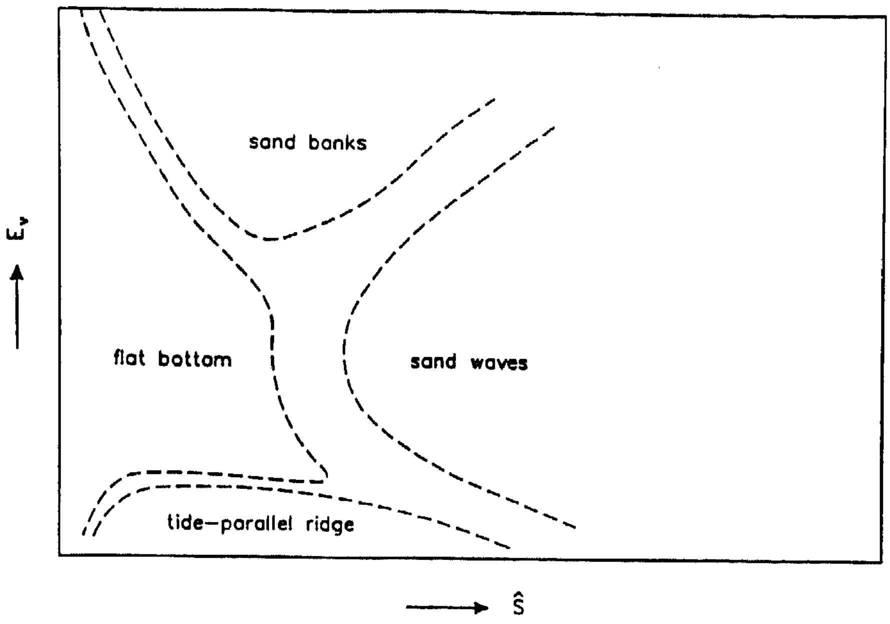

Figure 1. Characteristic bed forms predicted by the three-dimensional shallow water model as a function of the parameters s and E.

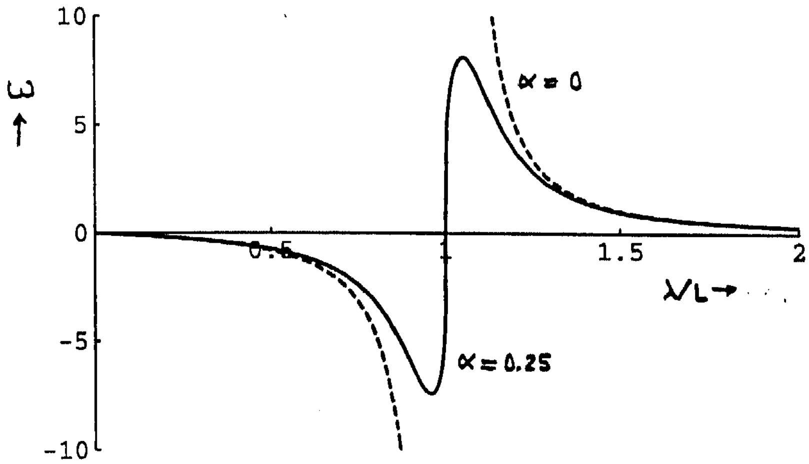

Figure 2. Growth rate ω of bed forms with wave-length L in the Boussinesq model, with λ the repetition length and α the ratio of λ and the frictional length scale.

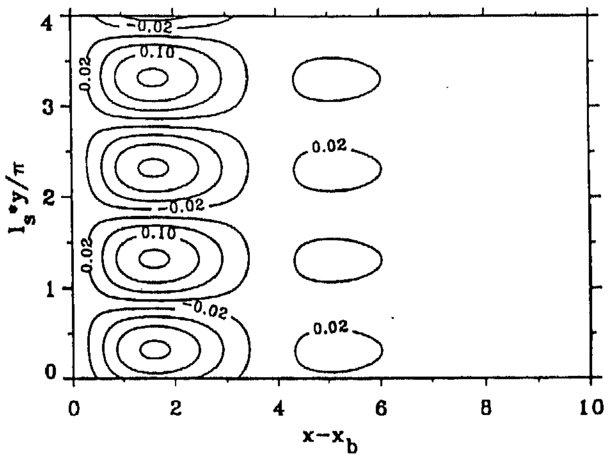

Figure 3. Contour plot of the steady free surface generated by the interaction between an incoming wave and a synchronous edge wave.