Deutsche Hydrographische Zeitschrift
German Journal of Hydrography
Volume 49 (1997) Number 2/3

ISSN 0012-0308

Evolution of Marine Morphodynamic Modelling: Time for 3-D?

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Summary

The question whether it is time for marine morphodynamic models to take into account the 3-D nature of water and sediment motion is discussed starting from practical demand and the state-of-the-art in basic knowledge and model development. This leads to the observation that there is a clear practical demand, and that suitable software environments and some 3-D model components exist, but that the basic knowledge on 3-D morphodynamic processes and the necessary know-how for utilizing these models are still insufficient. Hence it is concluded that there is an urgent need for modelling-oriented research on 3-D marine morphodynamics, but that it is too early to develop modelling facilities for practical application.

Entwicklung mariner morphodynamischer Modelle: ist es an der Zeit für 3D? (Zusammenfassung)

Die vorliegende Arbeit befaßt sich mit der Frage, ob marine morphodynamische Modelle auch die Dreidimensionalität von Wasser- und Sedimentbewegungen berücksichtigen sollten und geht dabei auf die bestehende Nachfrage sowie auf den heutigen Entwicklungsstand der Modelle ein. Sie gelangt zu dem Schluß, daß zwar eindeutig Nachfrage nach solchen Modellen besteht und bereits geeignete Software- und 3D-Modellkomponenten vorhanden sind, aber die Kenntnisse über 3D-morphodynamische Prozesse und die Anwendung solcher Modelle bisher unzureichend sind. Es wird daraus gefolgert, daß ein dringender modellorientierter Forschungsbedarf zu marinen morphodynamischen 3-D-Modellen besteht, es aber für die Entwicklung von Modellen für die Praxis noch zu früh ist.

Introduction

The morphological behaviour of the sea bed and the coast, autonomous or in reponse to human interference, plays an important role in the management and development of the coastal zone. This is obvious for coastal defense, land reclamation, sand mining, the coastal response to sealevel rise, etc. Less obvious it may be for hydrocarbon mining (subsidence, pipelines), fisheries (e. g. in coastal lagoons), nature preservation, pollution control, tourism, etc. Outside Europe (Australia, South-Africa), heavy-mineral mining and even offshore diamond mining (Namibia) can be added to the list.

Marine morphodynamics is therefore a research issue all over the world. Yet, progress is relatively slow, due to the complexity of the nonlinear dynamic interaction of waves, currents, sediment motion and sea bed topography. As a consequence, the state of the art lags behind that of marine hydrodynamics, where regional-scale 3-D tidal current models are in operational use now. In spite of a clear demand for predictions of 3-D phenomena in marine morphodynamics, 3-D modelling is still poorly developed.

This paper describes the demand for 3-D marine morphodynamic predictions, and the state of the art in modelling, from a scientific and model development point of view. This leads to an assessment of the timeliness of developing to 3-D models.

What is marine morphodynamics?

The morphological state of the sea bed is a manifestation of dynamic interaction between waves, currents, sediment transport and bed topography (Fig. 1). The water motion, driven by wind, waves and tides, and the sediment motion associated with it respond to a given bed topography. On the other hand, they may give rise to erosion or accretion of the bed. But once the bed topography has changed, the water and sediment motion will also change, thus causing a different pattern of accretion and erosion, and hence another change of bed topography, water and sediment motion, etc. As a result, the bed topography is not necessarily in equilibrium with the water and sediment motion: it may be evolving towards a new equilibrium state, in response to a perturbation or a change in conditions, but it may also exhibit an inherently unsteady behaviour, in the form of more or less regular wave-like features (sand banks, sand waves, nearshore bars, migrating channel/shoal systems).

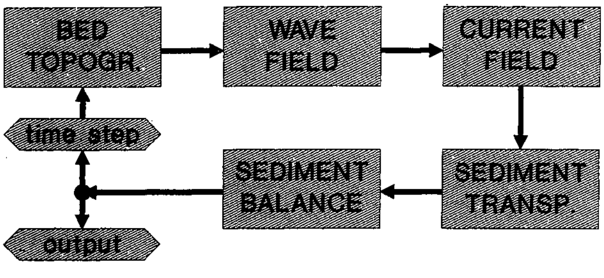

Fig. 1: Flow chart of the morphodynamic interaction

Fig. 2 shows an example of the latter behaviour: a sandwave field near the Euro-platform, in the North Sea off Rotterdam. Note that the dimensions of the picture shown are some 10 by 10 km. The sandwaves are up to 8 m high, at a water depth of 30 m, and have a wave length of a few hundred metres. Their crests are more or less perpendicular to the main tidal axis. The migration speed is not known in this case, but there are estimates from other fields of some metres to some tens of metres per year (cf. STRIDE [1982]). The height-modulation along the crests suggests that the sandwave field in Fig. 2 is superimposed on a larger-scale tidal ridge system. Clearly, laying a pipeline through such an area involves the risk of denudation, free-span formation and even buckling (LANGHORNE [1978]). A quantification of this risk as a function of the depth of trenching would be a useful product of research, not only in order to be able to design less expensive new pipelines, but also to assess the risk to which existing pipelines and cables will be exposed if large amounts of sand are mined off the coast, e. g. for land reclamation projects.

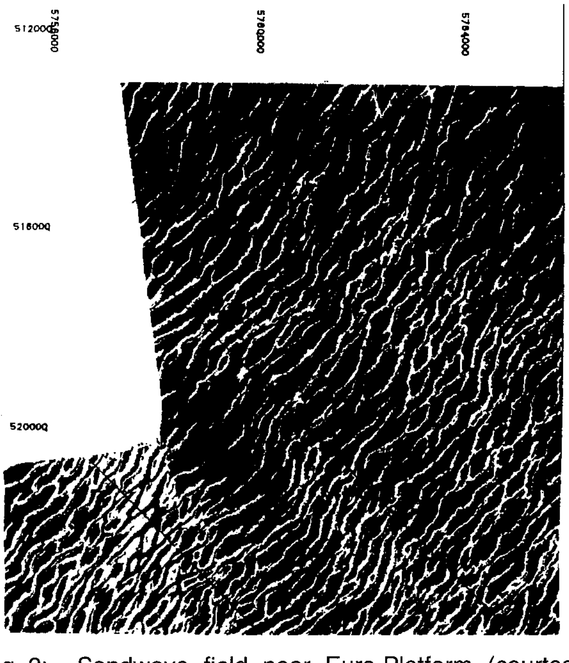

Fig. 2: Sandwave field near Euro-Platform (courtesy Rijkswaterstaat; see VAN GOOR AND ANDORKA GAL [1996])

Marine morphodynamics encompasses a number of zones of a different nature, viz. the shelf sea, the shoreface, the nearshore and, if there are coastal inlets, estuaries and coastal lagoons. In each of these zones, different mechanisms determine the morphological evolution.

The shelf sea water motion is usually dominated by astronomical and/or meteorological tides (Baltic), the sediment transport rates are usually small and morphological processes proceed slowly (millennia-scale). For further reference, see WRIGHT [1995].

On the shoreface, the influence of nonbreaking waves is added to this. These waves are rather effective in stirring sediment, especially in shallower water. Hence the transport rates are usually higher than on the shelf, but still not very high. This zone forms the transition between the shelf and the nearshore, and the morphological time scale ranges from centuries to decades. For further information on shoreface processes, see WRIGHT [1995].

Breaking waves play a dominant role in the subaqueous part of the nearshore zone (the beach). They stir large amounts of sediment, which is moved around by net currents and other mechanisms. This zone is morphologically very active, on time scales ranging from days to decades. The nearshore zone also includes a subaerial part (dry beach, dunes), where the transport is partly wave-dominated, partly wind-dominated. Here we find a strong asymmetry between the time scales of erosion (hours) and accretion processes (years). For an extensive description of surfzone mechanisms, see FREDSOE AND DEIGAARD [1992].

Estuaries and coastal lagoons can be tide-dominated, but they can also be subject to a mixture of tides, wind-driven currents and waves. Moreover, there can be strong salinity gradients, which drive another type of water motion (estuarine circulation). The predominant type of sediment can be sand or mud, or both. This may give rise to complicated morphological processes on a variety of time scales (days to centuries).

In each of these zones there is a variety of economic and environmental interests. Exploitation of marine resources can have a significant morphological impact. Fisheries in the North Sea, for instance, make sure that every square metre of the sea bed is ploughed several times per year. Massive mining of shoreface sand not only increases the risk of exposure of pipelines and cables, but it may also be a threat to the coast. On the other hand, human interference may give rise to morphological changes which are detrimental to the environment (e. g. rapid accretion, changes in depth zonation).

Table 1 gives a selection of economic interests in which the sea bed dynamics plays an important role.

Table 1

Zonation and economic interests

zone	economic interests
shelf sea	oil industry (exploration, pipelines, oil rigs) navigation channels tracking of pollutants sand mining dredged material disposal fisheries
shoreface	see shelf seas, and coastal protection land reclamation
nearshore	coastal defense tourism nature reserve (dunes)
estuaries and coastal lagoons	harbours and access channels ecosystem (nursery, feeding, resting) fisheries and aquaculture land reclamation sand mining hydrocarbon mining (Wadden Sea)

Apart from the above zonation, marine morphodynamics concerns a wide range of spatial and temporal scales, from turbulence on a second/millimetre scale to large-scale coastal behaviour at a scale of millennia and many kilometres (Fig. 3). Although there is probably a certain ordering (e. g. LARSON AND KRAUS [1995]), the scales are not totally separated: processes at different scale levels may influence each other. This is obvious for the top-down influence: phenomena on larger scales constitute the extrinsic conditions for phenomena on smaller scales. However, there are also various instances of bottom-up influencing. Examples are the effects of bedforms (ripples, megaripples) on the current pattern, the effects of wave breaking on nearshore circulations, and the effect of nearshore bars on coastal erosion (LIPPMANN et al. [1993]). Dealing with these scale interactions is one of the major challenges of morphodynamic modelling.

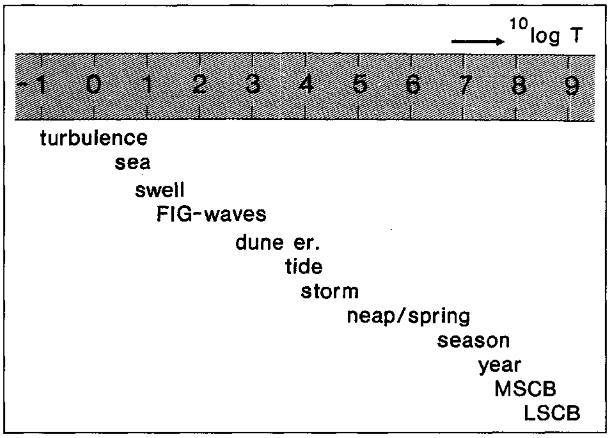

Fig. 3: Scale range of coastal dynamics (T = time, FIG-waves = far infragravity waves, MSCB = medium-scale coastal behaviour, LSCB = large-scale coastal behaviour)

Demand for prediction capability in 3-D

The prediction of various marine morphological phenomena requires 3-D modelling. The response to engineering works, such as groynes and breakwaters, is 3-D in nature because both the cross-shore profile and the longshore morphology are affected. Even the case of an elongated shoreface nourishment at Terschelling, The Netherlands, turns out to be 3-D, due to significant updrift and downdrift end-effects (HOEKSTRA et al. [1996]).

Nearshore bar systems develop 3-D patterns, especially during calm periods between storms (LIPPMAN AND HOLMAN [1990]). The description of bar formation requires a model which resolves the vertical structure of the water motion. Combined with the longshore non-uniformity, this leads to a 3-D current pattern. Also on a larger scale, bar systems may develop (WIJNBERG AND TERWINDT [1995]), often with their crest at an oblique angle to the shore (Fig. 4). Whether or not their modelling requires a 3-D current model is still under dispute.

An example of a strongly 3-D morphodynamic system is a tidal inlet with its complex and variable geometry of channels and shoals. This geometry is too complex to distinguish between cross-shore and longshore mechanisms at every point, if only because it is hardly possible to identify a meaningful orientation of the coast. WANG et al. [1991] have shown that resolving the vertical flow and sediment transport structure is a necessity in models of such systems. Even more complicated are tidal inlets with man-made structures (e. g. groynes), which may introduce 3-D phenomena on a different scale (e. g. scour holes).

The residual sediment transport on the shoreface is due to 3-D currents, driven by the tide, wind and horizontal density gradients in combination with the Coriolis effect (VAN RIJN et al. [1995]). This three-dimensionality has to be taken into account in long-term coastal models which include the shoreface.

Sandwaves tend to have their crest orientation perpendicular to the principal tidal axis, but the tidal motion on the open sea is seldom planar. This means that a sandwave model should be able to deal with 3-D currents (cf. HULSCHER [1996]).

In summary, there is a distinct practical demand for models which include 3-D effects in all zones of Table 1. Whether they have to be fully 3-D, or simpler variations (e. g. 22-D or quasi-3D), is the modeller's decision. In any case, 3-D is not just a refinement to existing lower-dimensional models but a necessity when describing certain important morphological phenomena.

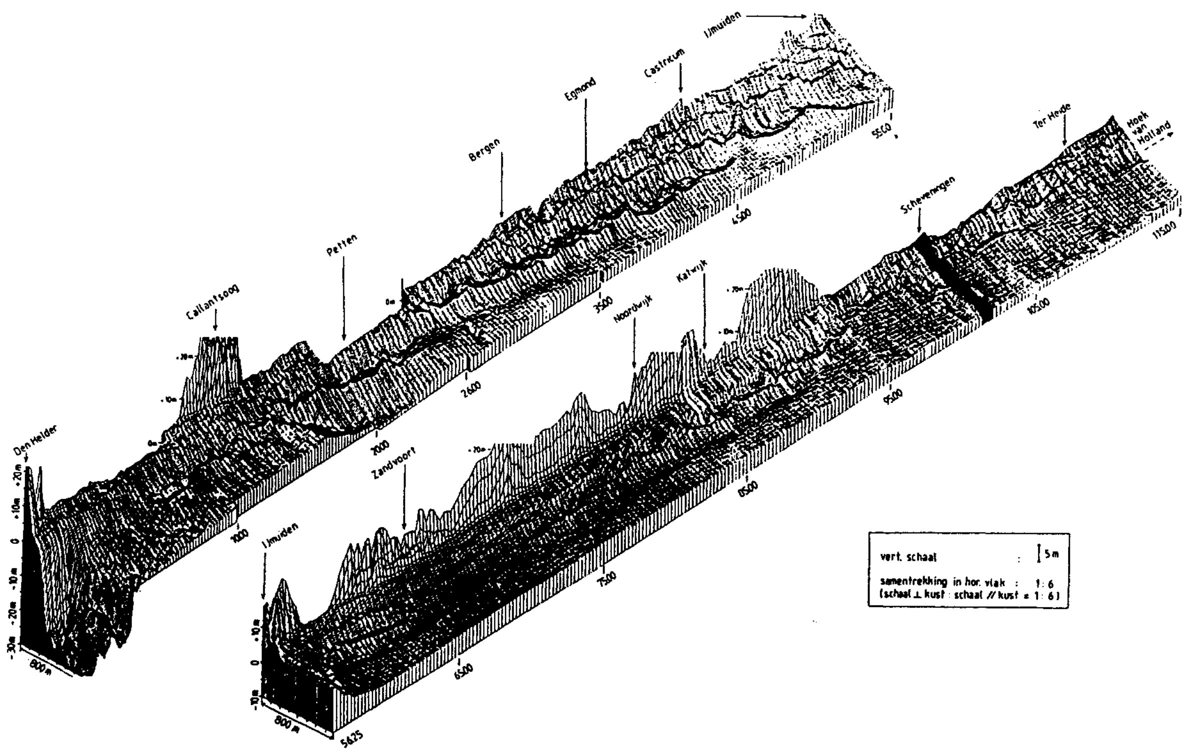

Fig. 4: Oblique bar system on the Holland coast (cf. DE VROEG et al. [1988])

Prediction capability available

The availability of models which are up to the above tasks is rather meagre. 3-D hydrostatic tidal models are available for applications on regional and smaller scales, but they concern only tidal and wind-driven currents and have hardly been tested so far in morphodynamic model systems.

Wave-driven current modelling has not yet advanced to 3-D models for practical use. Important problems which hamper the development of such models are the formulation of wave-induced forcing (DEIGAARD AND FREDSOE [1989]; DE VRIEND AND KITOU [1990]), the modelling of turbulence and 3-D boundary layer phenomena under waves and currents (e.g. SVENDSEN AND PUTREVU [1990]; also see FREDSOE AND DEIGAARD [1992]), and especially their empirical validation. Synoptic laboratory data on 3-D wave-induced currents and sediment transport are scarce, and comprehensive field data giving synoptic information on current and transport patterns in the surf zone are practically absent.

Fig. 5 shows the relevance of 3-D current modelling near man-made structures, in this case a detached breakwater on laboratory scale. The left part of the figure shows the depth-averaged current pattern. The near-bed current velocity and the bed shear stress according to this model show the same pattern, though with a different magnitude of the vectors. The right part of the figure shows the near-bed velocity from a 3-D hydrostatic current model (PÉCHON et al. [1997]). As far as the wave effects are concerned, this model can be considered a "three-dimensionalized" version of a number of 2-D concepts, with rather simple turbulence and bed shear stress submodels.

Most of the work which has been done on process-resolving nearshore morphodynamic modelling concerns either 2-D depth-averaged (2-DH) models, or 12-D cross-shore "slice"-models. In the former type of model, the vertical structure of the flow, including phenomena such as undertow, is not explicitly taken into account. The latter type is based on the assumption of longshore uniformity, often ignoring the longshore current, although the longshore current velocities may be an order of magnitude greater than the cross-shore ones. Longshore and cross-shore currents on a uniform beach interact directly via bed shear stress and turbulence production, and indirectly via the sediment transport (ROELVINK AND BROKER [1993]).

Both cross-shore profile and 2-DH modelling have made significant progress in recent years, under the impulse of – amongst others – the EU-programme Marine Science and Technology (MAST). In spite of the almost infinite variety of cross-shore transport mechanisms, coastal profile models have succeeded to some extent in explaining the formation and evolution of shore-parallel bars (ROELVINK AND BROKER [1993]), and they do a reasonable job in predicting the effectiveness of elongated nourishment (ROELVINK et al. [1995]), apart from 3-D end-effects. Coastal profile models are, therefore, a good testing ground for further research on morphological processes due to cross-shore transport mechanisms.

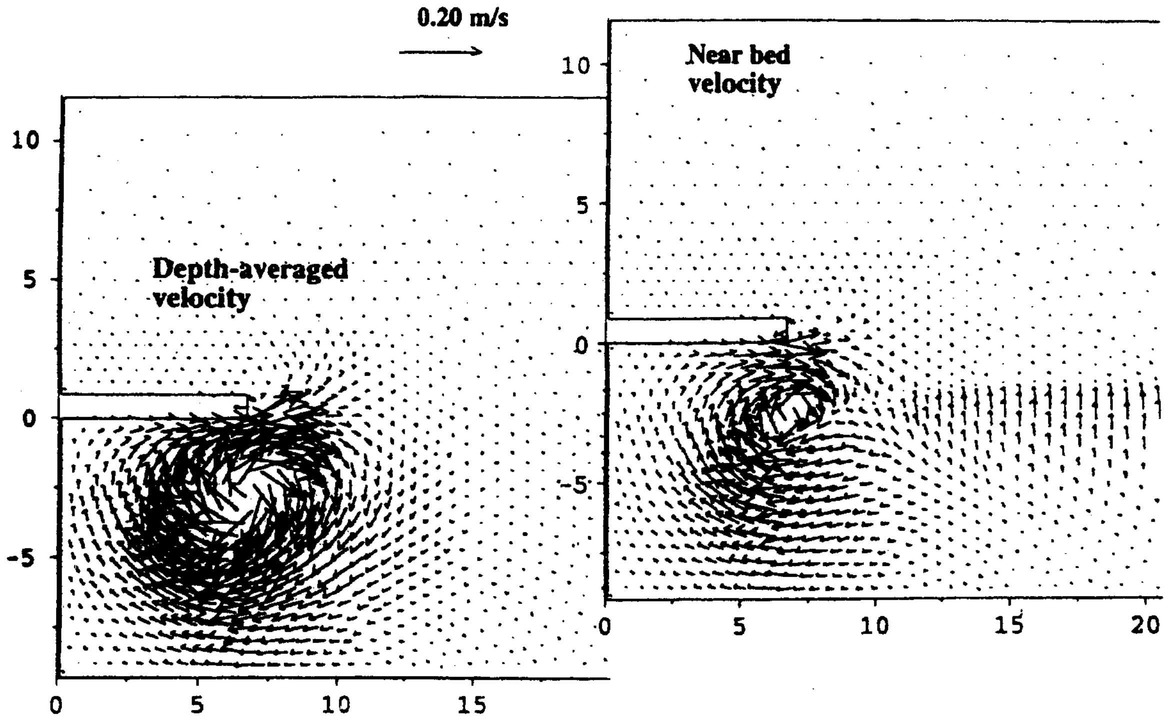

Fig. 5: Near-bed velocity behind a detached breakwater (cf. PÉCHON et al. [1997])

2-DH coastal area models seem to have overcome the initial problems concerning model composition, software organization and numerical technique. They are now being used in practice (e.g. RIBBERINK et al [1995]; BROKER et al. [1996]), but they are still rather time-consuming: a run-time of 50% of the real time is not exceptional. This is a practical reason why these models are not used for longer-term predictions (decadal scale and further).

2-D morphodynamics turns out to be much more complex than just a combination of known 1-D longshore and cross-shore processes. Even though "cross-shore" transport mechanisms associated with the vertical flow structure (e.g. undertow) are usually ignored, the system turns out to allow for a variety of rhythmic features. Fig. 6 shows the morphology after some time in the aforementioned case of a detached breakwater. Apart from the expected salient formation behind the breakwater, oblique bar systems develop, which may well become critical for the numerical process. An analysis of this phenomenon (DAMGAARD CHRISTENSEN et al. [1994]) revealed that it is inherent to the system of constituting equations.

The above leads to the following observations:

1) coastal profile models and 2-DH coastal area models are being used in practice, but separately; the build-up of confidence and experience, therefore, concerns only part of the 3-D morphodynamic phenomena,
2) cross-shore transport mechanisms greatly increase the complexity of the system and introduce a variety of new phenomena,
3) 2-DH models encompass a much richer morphodynamical behaviour than that found from 1-D longshore and cross-shore models,
4) at the moment, deterministic 2-DH model applications on the event scale are already time-consuming, let alone decadal-scale applications which do justice to the stochastic nature of the input.

3-D models must, therefore, be expected to lead to a substantial further increase in complexity and computer-power demand. For this reason, and because of their poorly developed theoretical backing (see below), they are still beyond practical applicability.

Theory

Complex morphodynamic models, in any number of spatial dimensions, cannot be used without a good background knowledge of the underlying processes and their interactions. A consistent build-up of theoretical knowledge is, therefore, of vital importance. This can be achieved by analyses of the mathematical system, e.g. characteristics analysis (De Vriend [1987a, 1987b]), inherent stability analysis, linear and nonlinear (De Vriend et al. [1993]; Hulscher [1996]; FalquJs et al. [1996]), and analysis of the equilibrium state (De Vriend et al. [1993]). Such analyses have been performed for 2-DH models, but hardly for 3-D models. As a consequence, the theoretical basis for 3-D morphodynamic modelling is still very thin.

Hulscher [1996] describes a stability analysis of a horizontal seabed exposed to a three-dimensional tidal motion. The current model used is essentially 3-D, although it assumes harmonic solutions in the horizontal and actually solves a coupled set of 1-D equations in the vertical. The turbulence

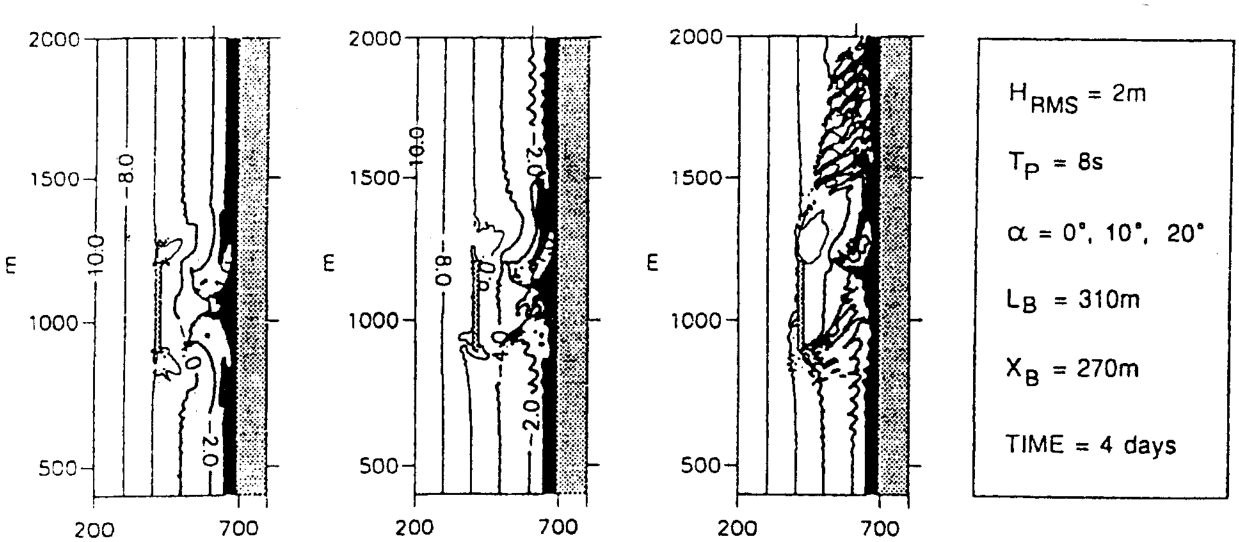

Fig. 6: Bed topography behind a detached breakwater (cf. Johnson et al. [1995]);
[spatial scales and depth values in m; HRMS = rms wave height, TP = peak wave period, ° = angle of wave incidence with respect to shore normal, LB = breakwater length, XB = distance from breakwater to the shoreline, TIME = real time elapsed since the simulation started with a plane sloping bed]

model boils down to a constant eddy viscosity, combined with a partial-slip condition on the bed, which means that the bottom boundary layer is not resolved. Yet, the introduction of the third dimension leads to much richer morphodynamic behaviour than in a 2-DH model: new features (sand waves, tide-parallel ridges) emerge, which are apparently associated with the response of the velocity profile to perturbations in the bed topography. The initial growth rate of these features is much greater than that of the larger-scale tidal sandbanks, which are associated with the 2-D depth-averaged response of the flow field (cf. HUTHNANCE [1982]).

VITTORI AND BLONDEAUX [1992] describe the 3-D dynamic interaction of bed perturbations with the near-bed boundary layer flow under short waves. They conclude that this leads to the onset of ripple formation, i. e. rhythmic features on yet another scale, much smaller than that of sandwaves or tidal ridges.

The picture which arises from these observations is that of a cascade of scales of rhythmic seabed features, where every step in the scale level of the hydrodynamic and/or sediment transport processes triggers features on another scale (Fig. 7). This picture is greatly complicated by the role of waves, which involve a variety of mechanisms of bar formation, especially in the nearshore.

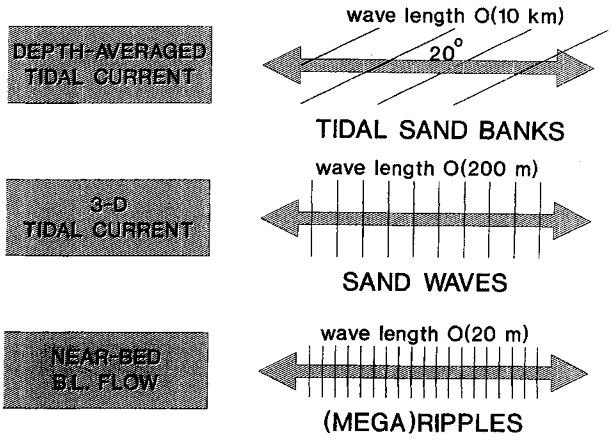

Fig. 7: Degree of hydrodynamic model detail vs. seabed features
(B. L. FLOW = boundary layer flow)

At this moment, there is no indication that all possible features have been identified, nor that the features which have been identified are realistic and correctly predicted by the present models. Hence we must conclude that refinement of the hydrodynamic and/or sediment transport model is likely to yield an increased complexity of the morphodynamic phenomena. This means that more research has to be done in order to establish a sound theoretical basis for 3-D morphodynamic model applications.

The analysis of the equilibrium state in a given situation provides additional information, irrespective of whether it is ever reached in reality. It reveals the state to which the system ultimately tends. If this does not match the expectations – based on experience or measured data – the model needs to be improved.

The equilibrium state of a 2-DH model of a straight beach is basically indifferent (cf. DE VRIEND et al. [1993]). As long as the transport is shore-parallel with zero longshore gradients, any cross-shore profile is in equilibrium. In order to have a non-arbitrary equilibrium state, it is necessary to include cross-shore transport mechanisms, such as wave asymmetry, undertow and the downhill gravitational transport.

This downhill transport component can easily be included into a 2-DH model, but this is not sufficient to explain the existence of a sloping beach: the equilibrium state near a fixed shoreline is a horizontal bed. Therefore, 2-DH nearshore morphodynamic models are probably not good enough for very-long-term applications[1)].

In order to have a sloping beach, the most important onshore transport mechanisms have to be included. But then the model can only be realistic if the most important offshore transport mechanism, viz. undertow, is also included. To that end, the hydrodynamic model has to describe the 3-D near-

1) On the other hand, they proved (e. g. HOEKSTRA et al. [1996]; BROKER et al. [1996]) to be good enough to describe the response to engineering works, such as groynes, breakwaters, dredged channels, etc., at time scales which are much smaller than the time needed to reach equilibrium (event-scale, annual scale).

shore current field. This does not imply that it has to be a fully-3D model which provides numerical solutions on a 3-D grid. 22-D or quasi-3D models, which combine a 2-DH circulation model (given the relationship between the bed shear stress and the depth-averaged velocity) with a 1-DV description of the velocity profile (given the depth-averaged velocity field), may perform equally well in a wide range of situations.

At first sight, it may be tempting to use Lagrangian transport descriptors in these complex flows. As long as the sediment properties are assumed to be uniform, however, morphological changes are computed more easily from a Eulerian sediment balance, on the basis of Eulerian sediment fluxes instead of individual grain displacements.

Experience

Morphodynamic modelling means that wave, current and sediment transport models are coupled via the sediment balance and the bed topography. In order to be coupled efficiently, these modules have to be made compatible at the software level and they have to be brought under a morphodynamic steering module. It may be tempting to start from well-established, but mutually incompatible software packages, e. g. because they are backed by wave/current/transport specialists. Experience has shown that this may lead to a laborious and time-consuming software restructuring exercise. This probably goes a fortiori for 3-D models.

The composition of such a compound model is far from trivial. Modules which seem to be good enough to describe wave height, current velocities and transport rates when applied separately, may exhibit spurious interactions when brought together into a morphodynamic model (e. g. DINGEMANS et al. [1987]). Also, the constituent model concept, however acceptable for separate application to the case, may be not good enough for morphology. Experience shows that morphodynamic modelling makes special demands on the constituent models.

The wave module, for instance, must include as many natural smoothing processes (irregularity, directional spreading) as possible, in order to avoid discontinuities, spurious circulations, and resonant interactions with the bed. The modelling of wave breaking, especially the spatial lag between the breaking point and the point where energy dissipation starts, may not be very critical to the wave height distribution, but it is absolutely critical to bar formation (ROELVINK AND BROKER [1993]). In certain cases, the advective terms in the momentum equations are not very important in the initial situation, but after some time, morphology usually develops in such a way that they become essential (cf. DE VRIEND [1987a]). Mean flow curvature, e. g. in tidal inlets, leads to weak secondary currents, but to dramatic morphological effects (WANG et al. [1993]). Lag effects in the suspended sediment concentration may be negligible when looking at the concentration field on the initial bed topography, but they can give rise to an important residual transport and thus play a key role in the morphodynamics (cf. BLACK et al. [1996]).

An adequate model composition, therefore, requires a thorough insight into the morphodynamic process. Combined with the observation that insight into 3-D morphodynamic processes is rather weak at the moment, this leads to the conclusion that 3-D morphodynamic modelling for practical purposes is still “a bridge too far”.

Another aspect of predictive modelling, in any number of dimensions, is how to deal with the natural variability of the input conditions. The weather is a major driving force of coastal behaviour, but it cannot be predicted in a deterministic sense. The system is nonlinear, so a spectral approach based on linear superposition of Fourier components is probably not totally adequate. Moreover, nonlinearity means that the sequence of events may play a role (cf. SOUTHGATE [1995]). These qualitative statements are theoretically true, but they have hardly been quantified for practical situations. Therefore, we are still largely in the dark about how important these effects are and how they work out.

A methodology for the rigorous treatment of uncertainty in morphodynamic model predictions is virtually non-existent. This is one of the most urgent research issues in coastal morphodynamic modelling. As long as this is not available, one must wonder whether investment into 3-D modelling tools for practical use is worthwhile.

Conclusion

In summary, we can conclude that there is a distinct practical need for morphodynamic models based on descriptions of the 3-D water and sediment motion, but that the state of the art is not yet advanced far enough to produce a robust tool for practical application at this moment. Moreover, the basic understanding of 3-D morphodynamic processes is still insufficiently developed to have a sufficient scientific backing of such applications.

Research efforts on 3-D morphodynamic modelling should, therefore, be increased now, primarily with the objective of developing a basic understanding of the morphodynamic processes, and a methodology for dealing with uncertainty (not only for 3-D models). The development of tools for 3-D morphodynamic modelling for practical purposes should only come second.

Acknowledgement

The views which are laid down in this paper are inspired to a large extent by the work done in the EU-funded MAST-projects "G6 Coastal Morphodynamics" (contract MAST 0035-C), "G8 Coastal Morphodynamics" (contract MAST2-CT920027) and "PACE" (contract MAS3-CT950002).

References

Black, K. P., R. M. Gorman, and G. Symonds, 1996: Sediment transport near the break point associated with cross-shore gradients in vertical eddy diffusivity. *Coastal Engineering*, **26**(3/4), 153–175.

Brrker, I., J. Zyserman, and P. R. Jakobsen, 1996: Thyborn coastal investigation 1995: new lessons from an old coastal problem. In: B. L. Edge (Editor): Coastal Engineering 1996, ASCE, New York, p. 4703–4716.

Damgaard Christensen, E., R. Deigaard, and J. Fredsoe, 1995: Sea bed stability on a long straight coast. In: B.L. Edge (ed.): Coastal Engineering '94, ASCE, New York, 1865–1879.

Deigaard, R. and J. Fredsoe, 1989: Shear stress distribution in dissipative water waves. *Coastal Engineering*, **13**, 357–378.

De Vriend, H. J., 1986: 2DH computation of transient sea bed evolutions. In: B. L. Edge (ed.), Coastal Engineering 1986 Proc., ICCE, New York, 1689–1712.

De Vriend, H. J., 1987a: 2DH mathematical modelling of morphological evolutions in shallow water. *Coastal Engineering*, **11**(1), 1–27.

De Vriend, H. J., 1987b: Analysis of 2DH morphological evolutions in shallow water. *J. Geoph. Res.*, **92**(C4), 3877–3893.

De Vriend, H. J. and N. Kitou, 1990: Incorporation of wave effects in a 3D hydrostatic mean current model. In: B. L. Edge (ed.): Coastal Engineering 1990 Proc., ASCE, New York, 1005–1018.

De Vriend, H.J., J. Zyserman, J. Nicholson, Ph. Péchon, J. A. Roelvink, and H. N. Southgate, 1993: Medium-term 2-DH coastal area modelling. *Coastal Engineering*, **21**(1-3), 193–224.

De Vroeg, J. H., E. S. P. Smit, and W. T. Bakker, 1988: Coastal Genesis. In: B. L. Edge (ed.), Coastal Engineering 1988 Proc., ASCE, New York, 2825–2839.

Dingemans, M.W., A. C. Radder, and H. J. De Vriend, 1987: Computation of the driving forces of wave-induced currents. *Coastal Engineering*, **11**(5 and 6), 539–563.

FalquJs, A., A. Montoto, and V. Iranzo, 1996: Bed-flow instability of the longshore current. *Cont. Shelf Res.*, **16**(15), 1927–1964.

Fredsoe, J. and R. Deigaard, 1992: Mechanics of Coastal Sediment Transport. *Adv. Series on Ocean Eng.* – Vol. **3**, World Scientific, Singapore, 369 pp.

Hoekstra, P., K. T. Houwman, A. Kroon, B. G. Ruessink, J. A. Roelvink, and R. Spanhoff, 1994: Morphological development of the Terschelling nourishment in response to hydrodynamic and sediment transport processes. In: B. L. Edge (Editor): Coastal Engineering 1996, ASCE, New York, 2897–2910.

Huthnance, J. M., 1982: On one mechanism forming linear sand banks. *Est.,Coastal and Shelf Sci.*, **14**, 79–99.

Hulscher, S. J. M. H., 1996: Tidal-induced large-scale regular bed form patterns in a three-dimensional shallow water model. *J. Geoph. Res.*, **101**(C9), 20727–20744.

Johnson, H., I. Broker, and J. A. Zyserman, 1995: Identification of some relevant processes in coastal morphological modelling. In: B.L. Edge (ed.), Coastal Engineering '94, ASCE, New York, 2871–2885.

Langhorne, D.N., 1978: Offshore engineering and navigational problems – the relevance of sandwave research. Soc. Underwater Techn./Inst. Ocean. Sci., London, 21 pp.

LARSON, M. AND N. C. KRAUS, 1995: Prediction of cross-shore sediment transport at different spatial and temporal scales. *Marine Geol.*, **126**, 111–127.

LIPPMANN, T.C. AND R. A. HOLMAN, 1990: The spatial and temporal variability of sand bar morphology. *J. Geoph. Res.*, **95**(C7), 11575–11590.

LIPPMANN, T.C., R. A. HOLMAN, AND K. K. HATHAWAY, 1993: Episodic, nonstationary behaviour of a double bar system at Duck, NC, USA, 1986–1991. *J. Coastal Res.*, **15**, 49–75.

RIBBERINK, J.S., E.H. NEGEN, AND G. HARTSUIKER, 1995: Mathematical modelling of coastal morphodynamics near a tidal inlet system. In: W. R. Dally and R. B. Zeidler (eds.): Coastal Dynamics '95, ASCE, New York, 915–926.

PÉCHON, P., F. RIVERO, H. JOHNSON, T. CHESHER, B. A. O'CONNOR, J.-M. TANGUY, T. KARAMBAS, M. MORY, AND L. HAMM, 1997: Intercomparison of wave-driven current models. *Coastal Engineering*, **31**(1–4), 199–215.

ROELVINK, J.A. AND I. BROKER, 1993: Cross-shore profile models. *Coastal Engineering*, **21**(1–3), 163–191.

ROELVINK, J.A., TH. J. P. G. MEIJER, K. HOUWMAN, R. BAKKER, AND R. SPANHOFF, 1995: Field validation and application of a coastal profile model. In: W. R. Dally and R. B. Zeidler (eds.): Coastal Dynamics '95, ASCE, New York, 818–828.

SOUTHGATE, H.N., 1995: The effects of wave chronology on medium and long term coastal morphology. *Coastal Engineering*, **26**(3/4), 251–270.

STRIDE, A.H., 1982: Offshore tidal sands: processes and deposits. London: Chapman and Hall, 222 pp.

SVENDSEN, I. A. AND U. PUTREVU, 1990: Nearshore circulation with 3-D current profiles. In: B. L. Edge (ed.), Coastal Engineering 1990 Proc., ASCE, New York, 241–254.

VAN GOOR, S. AND J. H. ANDORKA GAL, 1996: Bodem. Rijkswaterstaat, RIKZ document RIKZ/OS-96.109X, 28 pp (in Dutch).

VAN RIJN, L. C., A. RENIERS, T. ZITMAN, AND J. S. RIBBERINK, 1995: Yearly-averaged sand transport at the 20 m and 8 m depth contours of the Jarkus-profiles 14, 40, 76 and 103. Delft Hydraulics, Rept. H 1887, 101 pp.

VITTORI, G. AND P. BLONDEAUX, 1992: Sand ripples under sea waves, Part 3: brick pattern ripple formation. *J. Fluid Mech.*, **239**, 23–45.

WANG, Z.B., H. J. DE VRIEND, AND T. LOUTERS, 1991: A morphodynamic model for a tidal inlet. In: A. S.-Arcilla et al., *Computer Modelling in Ocean Engineering*, **91**, Rotterdam: Balkema, 235–245.

WANG, Z.B., T. LOUTERS, AND H. J. DE VRIEND, 1993: Morphodynamic modelling for a tidal inlet in the Wadden Sea. *Marine Geol.*, **126**, 289–300.

WIJNBERG, K. M. AND J. H. J. TERWINDT, 1995: Extracting decadal morphological behaviour from high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis. *Marine Geol.*, **126**, 301–330.

WRIGHT, L. D., 1995: Morphodynamics of Inner Continental Shelves. CRC Press, Boca Raton, FL, 241 pp.

Submitted: 07. 03. 1997
Accepted: 10. 03. 1998

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