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Developments in coastal engineering research

Jurjen A. Battjes *

Department of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

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Abstract

This paper presents a review of recent advances in understanding and modelling of hydrodynamic and morphodynamic processes in the coastal zone as well as some challenges for further developments. Different processes are distinguished, and for each of these, essential characteristics of the state-of-the-art are mentioned, with emphasis on recent developments, as well as open questions that are considered important.

1. Introduction

At the request of the organisers of a symposium held in November 2003 in Tokyo, on the occasion of the 50th Anniversary of the Japanese Conference on Coastal Engineering, the author presented a keynote address giving an overview of progress and trends in coastal engineering research. The contents of that address are – in part and updated – contained in this paper.

In order to structure the appraisal of progress achieved and key problems to be addressed, a set of relevant aspects is identified and briefly dealt with in succession. We restrict ourselves to coastal hydrodynamics and morphodynamics. Structural and other aspects that are relevant in the broader domain of coastal engineering are not considered. Since many subjects are touched upon, references will be given only sketchy. Full state-of-the-art referencing per subject can be found in the literature cited.

2. Hydrodynamic processes and modelling

In this section we consider the principal categories of hydrodynamic processes, differing both in causative factors and (as a result) in characteristic time scale, and their modelling. Per category, relevance, recent advances and current needs will be pointed out.

2.1. Sea level

The current global trend of sea level rise receives much attention worldwide. New insights in the earth climate system emerge and new models are being developed. Despite large variation between model predictions, depending on the modelling as such and the chosen parameters and scenarios, there is general agreement that sea level rise is accelerating, with estimated amounts for the present (21st) century in the order of 0.5 m, although with a margin of as much as ± 0.3 m (IPPC, 2001). Sooner or later, this will have grave consequences for beach preservation, coastal protection, water management, etc., possibly with devastating results for low-lying areas.

Although research in the field of climate change and sea level rise is not part of coastal engineering research as such, the results are highly relevant and should stimulate further research to develop concepts and tools to anticipate the consequences and to deal with them in the development of sustainable coastal policies (Van Koningsveld and Mulder, 2004). The emphasis herein is not primarily technical but highly multi-disciplinary, a subject *par excellence* of Integrated Coastal Zone Management (ICZM).

2.2. Tides and storm surges

Computation of tides and storm surges, based on the depth-integrated shallow-water equations, is well established. Poorly defined quantities herein, needing calibration for applications in specific sea basins, are the empirically determined coefficients for the drag between wind and sea surface and between

* Fax: +31 15 2784842.
E-mail address: j.battjes@ct.tudelft.nl.

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the induced flow and the sea bed, and the influence thereon of the deforming interfaces, i.e. due to wave generation at the sea surface and formation of ripples or dunes (or a flat bed) at the bed, respectively.

For low-lying coastal areas that are not protected by natural dunes or man-made dikes, or insufficiently so, overland flooding may occur. From a hydrodynamic point of view, such flows involve three different types of transitions: those between wetted areas and dry land, between one-dimensional (1D) flow in conduits and two-dimensional (2D) flow, and between subcritical and supercritical flow. A robust and accurate numerical code has been developed for the representation of these phenomena (Stelling et al., 1998; Stelling, 2000). The model is specially suited to simulate the dynamic behaviour of overland flow over initially dry land, as well as flooding and drying processes on every kind of geometry, including lowlands and mountain areas. It also gives accurate and stable results in computations of flow on very steep slopes such as dikes. The 2D-model has been coupled to an existing 1D model, allowing full exchange between the two flow types, such as occurs in flooding and drying of low rural areas dissected by ditches, canals, creeks, rivers, etc., as well as in urban areas with storm water sewage systems.

The package can be used for flood simulation, damage assessment and risk evaluation for coastal areas, river valleys, mountain areas and lowland areas. The flow module is used to determine the flooded area at GIS pixel level including the water depth and inundation period. Damage assessment is possible, provided that sufficient data of land use and investments are available within a GIS system. For operational purposes, e.g. generation of information needed for decisions for evacuation, the results can be used within a Decision Support System.

The flow simulation package Delft-FLS as described by Stelling (2000) has recently been verified against observations of flow over a horizontal concrete bottom in a laboratory basin, following a simulated dike breach (Stelling and Duinmeijer, 2003). The observed rate of progress of the advancing and laterally spreading front as well as the ensuing water depth variation in time was very well reproduced by the model, both for flooding of an initially dry bed and in case of inflow into an initial shallow layer of stagnant water. Fig. 1 shows an example of the latter situation.

A long-term problem in the area of storm surges and associated coastal flooding concerns the effect of climate changes on the frequency, intensity and track pattern of storms. Present results indicate a trend of increasing intensity both in wind speed and in rainfall. Systematic long-term monitoring is necessary.

2.3. Large-scale coastal currents

Coastal seas experience the effects of river borne sediment, biota, nutrients and pollutants. The ensuing discharge of estuarine water into coastal seas results in the formation of river plumes. In the Northern Hemisphere, the outflowing estuarine waters tend to turn to the right on leaving the river mouth, forming narrow coastal conduits for the transport of fresh water and matter. River plumes can maintain their identity and cross-shelf structure for hundreds of kilometres alongshore and, as such, are important in determining the transfer of matter and the fate of pollutants in coastal seas (see Fig. 2 for the sediment-laden Po plume, stretching along the entire Italian Adriatic coastline; Kourafalou (2001) presents a dynamical analysis of this plume system). River plumes resulting from localised sources of buoyancy along our coastlines represent one of the principal forcing mechanisms for coastal and shelf currents. It is an underrated phenomenon in coastal engineering.

McClimans (1986) identified three major processes characterising the seaward expansion of the river flow. Acceleration, which is related to a hydraulic control at the river mouth resulting from a balance of inertia and gravity (buoyancy) forces, mixing processes, and geostrophic processes. As low

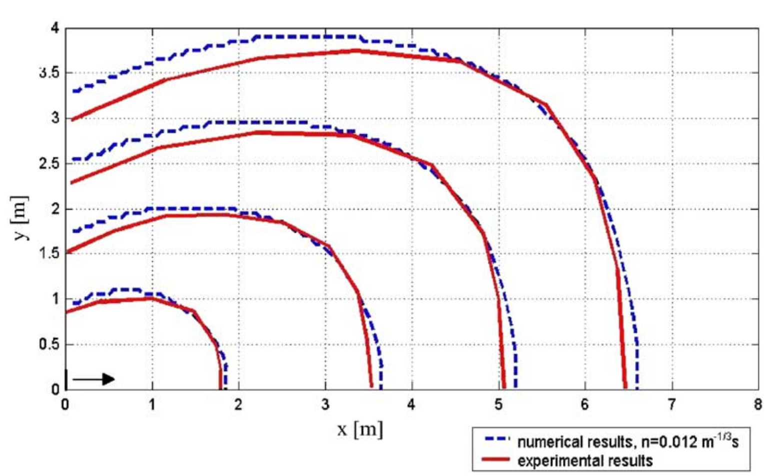

Fig. 1. Plan view showing positions of front of inundation surge on a horizontal bottom at times 1 s, 2 s, 3 s and 4 s after the sudden opening of a 40-cm-wide gate at $x=0$ in the centerline of the basin ($y=0$), extending from $y=-0.2$ m to $y=0.2$ m, allowing free flow out of a reservoir into the basin. Initial water depth = 5 cm, initial head difference = 55 cm. Only one-half of the basin is shown because of symmetry with respect to the centerline. Full line: (camera) observations; dashed line: results from numerical simulation with Delft-FLS (Stelling and Duinmeijer, 2003).

Fig. 2. Satellite-borne image of Italy and surrounding seas showing the sediment-coloured coastal plume of the Po River. Image provided by the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE; satellite = Orb-View-2; sensor = SeaWiFS (http://visibleearth.nasa.gov/cgi-bin/viewrecord?4958).

salinity water moves offshore, it is governed by the Coriolis force and sets up an alongshore current in geostrophic balance. Tidal straining has been shown to be an important process in regions of freshwater influence; see for example Simpson (1997). Recent studies try to characterise the role of wind and ambient currents in determining the behaviour of buoyant plumes (Kourafalou, 2001; Berdeal et al., 2002). Fong and Geyer (2002) pay attention to the dynamics at the mouth of the river and the influence of ambient currents.

At coastal boundaries, enhanced mixing can take place as a result of the conversion of kinetic energy from the tides into internal waves and vortices. These processes represent a mechanism for mixing stratified flows, thereby altering the structure and behaviour of a coastal plume. Pietrzak et al. (1990) suggested that internal waves could have a significant effect on turbulence production and mixing in stratified estuarine and coastal flows; it is a sub-grid process that needs to be parameterised in typical coastal and ocean models; see also Pietrzak and Labeur (2004).

Recent studies by MacCready and Pawlak (2001) investigate lee wave generation and horizontal flow separation along a slope with an isolated ridge and a corrugated slope. Pawlak and MacCready (2002) investigate oscillatory flow along a coastline with a series of headlands and ridges and demonstrate that momentum and mass can be transferred from the boundary to the interior flow through organised residual flow patterns. These phenomena are important when one considers the impact of introducing engineering structures into a coastal river plume, such as breakwaters or nearshore artificial islands. For instance, how do these change the stability of the plume with consequent impact on the transports and ultimate spreading of suspended matter, nutrients and pollutants?

The aforementioned processes are complex and place severe demands on both numerical models and observational systems. Casulli and Walters (2000) and Zhang et al. (2004) both present a three-dimensional hydrostatic unstructured grid model that appears suitable for these kinds of flows. The model by Zhang et al. (ELCIRC) is available online. An application of this model to the Columbia River outflow and plume is presented by Baptista et al. (2005). Ham et al. (2005) developed an unstructured grid model with enhanced grid flexibility. This forms part of an ongoing effort towards a new environmental fluid mechanics modelling system using the non-hydrostatic flow solver of Stelling and Zijlema (2003).

The smaller-scale, wave-induced surf zone currents are dealt with in following sections.

2.4. Episodic events

We briefly refer to some hydrodynamic phenomena that can be relevant in the coastal domain but which occur only episodically, being absent most of the time.[1]

Observations of the water elevation along the Dutch North Sea coast have for many years shown the incidental occurrences of so-called squall-induced pulses and squall-induced oscillations (Wemelsfelder, 1957; Delta Commission, 1960), i.e. a soliton-like pulse or a burst of oscillations with periods from, say 10 min to 1 h or so, superposed on the more slowly varying tide and wind set-up. They are occasionally apparent in the tidal records of coastal stations. In some cases, they are seen to travel along the coast. Pulses and oscillations are observed only in rough weather conditions, but their origin and propagation characteristics in the open sea have remained unknown until recently. Their possible contribution has to be taken into account in the sea surface elevation which is to be used in the design of coastal dikes, dunes and coastal defence structures in The Netherlands. This is done through the addition of a location-dependent height to the design water level resulting from tides and storm surge alone, typically a few decimeters along the open coast to more than half a meter in some basins.

The phenomena of squall-induced pulses and of squall-induced oscillations, or similar phenomena under different names, do not appear to have received much attention in the international literature. That is not true for another episodic phenomenon, in some cases related to the first, i.e. harbour seiching, which has frequently been observed and reported for numerous coastal harbours around the world. It is a nuisance factor because it can reduce access windows for deep-draught vessels, and it can hamper loading and offloading of moored ships, leading to downtime and possibly damage (broken mooring lines). Different physical mechanisms of generation of

[1] Tsunamis are not dealt with here. The author has no first-hand experience with them, and could do no justice to the subject, particularly in view of the recent devastating Indian Ocean tsunami.

harbour seiching have been identified in the past, including incidence of bound subharmonics of groupy short waves (Bowers, 1977), tsunamis, and atmospheric pressure variations (Vidal et al., 2000). Each port usually is predominantly affected by disturbances due to one of these sources.

Recently, it has been shown that meso-scale atmospheric convection cells, following a cold front passing over the North Sea, can induce a moving pattern of oscillations in wind stress and atmospheric pressure which generate low-frequency waves at the North Sea. These in turn give rise to resonant seiche response in harbours along the shores of the southern North Sea (De Jong and Battjes, 2004a,b). It is likely that the so-called "squall-induced oscillations" that have been observed through the years are also due to atmospheric convection cells.

2.5. Wind waves and swell

Wind-generated waves are the prime energy supplier to the nearshore area, generating currents and transporting sediments, so shaping our coasts. It is logical therefore that they are a prime subject of research in physical oceanography and coastal engineering, which has led to significant advances in understanding as well as modelling capability.

Prediction of wind waves in extensive areas such as oceans and shelf seas is only practically feasible in a phase-averaged sense. This has led to numerical models based on the spectral wave energy balance, with linear propagation and a set of source terms accounting for wind input, cross-spectral transfer and dissipation. The archetype model in this category is WAM (WAMDI Group, 1988; see also Komen et al., 1994), primarily developed for deep water, with some allowances for restricted depth. WAVEWATCH (Tolman, 1991) is a similar model, while the model SWAN, based on the same principles, is designed especially for shallow coastal regions (Booij et al., 1999).

The wind input formulation used in these models is based on a mix of theory and empiricism. This has led to useful, realistic results, but the determining processes are still poorly known. For instance, according to Tolman and Chalikov (1996), their integral wind input, which is optionally available in WAVEWATCH, is a factor two to three lower than the one by Snyder et al. (1981), whereas the formulation by Komen et al. (1984), which is commonly used in WAM, gives higher input than Snyder et al., particularly at the higher frequencies (Komen et al., 1994). Differences in input have been compensated by tuning of dissipation, and even the quadruplet interactions, so as to reproduce observed net growth rates. This is unsatisfactory from a scientific viewpoint.

The dissipation term in WAM, representing deep-water whitecapping, is based on the pulse model by Hasselmann (1974). Its strength depends strongly on a spectrally averaged wave steepness. It has been tuned for wind-driven sea. When applied to mixed sea-swell situations it predicts a lowered dissipation and therefore an enhanced net growth of the wind sea, compared to the wind sea in absence of swell. This is in contrast with laboratory observations (Donelan, 1987). Following Phillips (1985), Donelan and Yuan (1994) describe a model for whitecapping dissipation that is fully local in spectral space, not containing a spectrally averaged steepness, and therefore does not suffer from (an incorrect) swell influence on wind sea growth. It has been elaborated by Alves and Banner (2003) and implemented in the SWAN model by Van der Westhuysen et al. (2005).

A key process in the wind wave evolution is resonant quadruplet wave–wave interaction (Hasselmann, 1962). Due to the forbidding nature of the full integrals involved, various approximations have been devised. The commonly used so-called discrete interaction approximation (DIA) is relatively fast but also rather crude. Particularly the positive lobe, representing transfer to higher frequencies, is overestimated compared to more exact calculations (Tanaka, 2001). Alternative methods have been developed (Hashimoto et al., 1998, 2002; Resio and Perrie, 1991) but these are not (yet) commonly used operationally because of their greater demand on computer time.

In restricted depth, the deep-water values of the DIA are commonly enhanced with a depth-dependent factor that is constant across the spectrum, which is at variance with more exact evaluations (Van Vledder and Bottema, 2002). In particular, the zero-crossing positions between positive and negative lobes are not shifted if a frequency-independent scaling is used, whereas the more exact results indicate that these shift towards lower frequencies with decreasing relative depth.

In shallow water, triad wave–wave interactions become important, giving rise to bound super- and subharmonics. A crude, parameterised approximation for their effects on the wind-wave spectrum (not the subharmonics) is presently included in SWAN, but that appears to overestimate the transfer to the high frequencies. Phase-averaged energy models, based on first principles, specifically aimed at the effects of triad interactions on the wave field evolution, were developed by Herbers and Burton (1997) on the basis of Boussinesq theory and by Agnon and Sheremet (1997) based on fully dispersive linear theory while accounting for near-resonant triad interactions. In essence, these models involve transport equations both for the energy spectrum and for the bispectrum, but their formulation is restricted to parallel depth contours and wave conditions that are statistically uniform alongshore. There is a need to generalise this to the fully two-dimensional formulation.

For more restricted areas such as inshore regions, coastal harbours, etc., phase-resolving (deterministic) models become feasible. These are commonly based either on Boussinesq equations or on fully dispersive wave theory.

Boussinesq models can yield details of nonlinear waves over sloping bottoms (Peregrine, 1967), including effects of breaking (through incorporation of the roller concept or via enhanced diffusion), at manageable computation cost because of the depth-integrated formulation. They have been extended to cover higher degrees of nonlinearity as well as frequency dispersion (Wei et al., 1995; Gobbi et al., 2000). Madsen and Schäffer (1998) present a review. More recent contributions are given by Kennedy et al. (2000), Chen et al. (2000), Madsen et al. (2002). This development has been carried to what appears to be its limit by Madsen et al. (2003), whose model is fully nonlinear and has good dispersion even in quite deep water. Most operational Boussinesq models are in the time domain, but frequency-domain formulations can offer an attractive alternative (Bredmose et al., 2004).

Janssen et al. (in press) have developed deterministic evolution equations for the complex surface elevation amplitudes based on fully dispersive wave theory, involving uniformly valid (in any depth) formulations for quadratic and cubic wave–wave interactions; lateral depth variations are allowed provided they are relatively weak. (These evolution equations have recently been cast in stochastic form by ensemble averaging.) The ability of this model to simulate harmonic generation in nonlinear shoaling, refracting and laterally focussing waves is illustrated in Fig. 3, which shows a comparison between predicted and observed (Whalin, 1971) surface elevation amplitudes of the primary component and its first two harmonics of waves over a sloping, convex slope in a laboratory flume.

An efficient, powerful alternative to Boussinesq modelling consists of the conventional, depth-integrated shallow-water equations, extended with a module for the determination of the dynamic (non-hydrostatic) part of the fluid pressure, in addition to a division of the fluid domain in a number of layers. Originally developed for shallow flows with local non-hydrostatic behaviour (see Casulli and Stelling, 1998), it has since been extended to deal with surface waves even in relatively deep water (Stelling and Zijlema, 2003). Like VOF-models, it can handle shear flows and turbulence, but it is computationally considerably faster.

Because of the depth-integrated formulation and (therefore) the single-valuedness of the surface elevation as a function of horizontal position in Boussinesq-models and in the nonhydrostatic model of Casulli/Stelling/Zijlema, these cannot model overturning waves. Lagrangian methods are more suited for this purpose. The earliest models of this kind were based on potential flow theory, which allowed a reduction of dimensionality from that of the fluid domain to that of the boundary only, which has significant computational advantage.

Potential flow methods are not valid for the motion following the impact of the overturning wave into the trough ahead. That requires models allowing for shear flow and turbulence, and ideally even two-phase flow in view of the aeration taking place in breaking. VOF-models are suited for this purpose. These can in principle deal with overturning waves and even with splashes. An example is the model by Lin and Liu (1998), developed for studying the evolution of shoaling and breaking waves. It solves the Reynolds equations for the mean (ensemble average) flow field and the k-epsilon equations for the turbulence. Good agreement between numerical results and experimental data has been observed for shoaling and breaking cnoidal waves on a sloping beach in terms of free-surface profiles, mean velocities, and turbulent kinetic energy. Previously, Van Gent et al. (1994) reported a VOF-model that has been developed specially for interaction of waves with structures of arbitrary shape and/or permeability. The latter property makes it suitable for numerical studies of waves on permeable slopes for purposes of estimating dissipation and reflection, or stability of cover layer elements.

An interesting new development is the application of a discrete particle method to problems of water waves including aerated flows following wave breaking. This is a Lagrangian

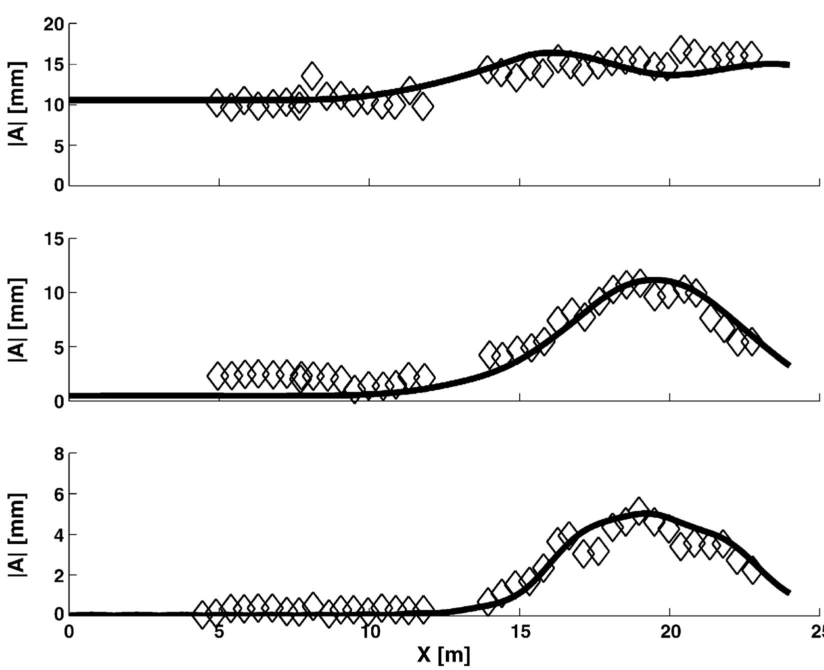

Fig. 3. Computed (curve) versus observed (diamonds) surface elevation amplitudes of primary component (top panel), first harmonic (middle panel) and second harmonic (bottom panel) for waves over a sloping, convex slope in a laboratory flume (Whalin, 1971); incident wave period = 2.0 s, height = 1.06 cm. Source: Janssen et al. (submitted for publication).

method, expressed in a set of coupled ordinary differential equations for a large number of interacting discrete particles, simulating the fluid motion according to the Navier–Stokes equations. It combines the advantage of exactly fulfilling the nonlinear free surface boundary conditions with the possibility to represent rotational flows and splashes. Koshizuka et al. (1998) and Gotoh and Sakai (2005—this issue) apply the so-called moving particle semi-implicit method (MPS) to breaking waves. Gómez-Gesteira and Dalrymple (2003) and Dalrymple and Rogers (2005—this issue) use the smoothed particle hydrodynamics (SPH) method to calculate wave interaction with structures. These methods are quite demanding in computation time, but they yield very realistic results.

2.6. Wave–current interactions

Wave propagation over long distances on uneven bathymetry and a given non-uniform large-scale current is conventionally described with a phase-averaged WKB-approximation, using the Doppler-shifted dispersion equation, kinematic equations for the wave phases, and a wave action balance equation to calculate the amplitudes (Mei, 1983). Wave effects on the current field are determined through the short-wave-averaged shallow-water equations with radiation stress forcing. Both sets of equations can be solved simultaneously to allow for mutual interactions. That is a well- established and routinely applied practice. Reference is made to Péchon et al. (1997) for a review.

In the approach described above, the pressure in the current is usually assumed to be hydrostatic and the current velocity vertically uniform. The SHORECIRC model (see e.g. Haas et al., 2003, for model description and application to rip current simulation) also uses the depth-integrated hydrostatic shallow-water equations for the current field, but it allows a vertically non-uniform current velocity (varying in strength and/or direction), which is computed through the use of shape functions. The contribution of the vertical variation of the velocity is included in the horizontal momentum balance through advective dispersion terms. Although based on 2D, depth-integrated equations, the model allows simulation of the gross features of the vertical variation of current velocity including effects of the surface waves. The feedback of this shear on the short-wave vertical structure and propagation is usually neglected, although expressions for its effect on the dispersion equation are known (see Thomas and Klopman (1997) for a summary).

A full three-dimensional current model combined with a WKB-wave description requires a depth-resolved formulation of the mean momentum flux delivered by the short waves, rather than the classical, depth-integrated expressions. Mellor (2003) derived such expressions for the vertically dependent radiation stresses, a definition of the Doppler velocity for a vertically dependent current field, vertically dependent surface pressure forcing and terms for production of turbulence energy by currents and waves. The analysis utilises the depth dependence of the wave motions as in the linear theory for uniform waves.

The effects of waves on the vertical current velocity profile need to be considered in detail in order to explain the counter-intuitive empirical observation that the surface velocity in a shear current is enhanced by waves propagating against the current, and vice versa. The mean vertical flux of horizontal momentum plays a key role here. Its estimation is sensitive to modelling assumptions, since it is zero in progressive waves of steady form. Nielsen and You (1996) gave a semi-quantitative explanation for this phenomenon in terms of wave contributions to the phase-averaged vertical flux of forward momentum. Groeneweg and Klopman (1998) and Groeneweg and Battjes (2003) present a model along the same lines for the two-dimensional (2D) and the three-dimensional (3D) case, respectively, in a fully quantified formulation using the Generalised Lagrangian Mean (GLM) formalism. The gradual wave energy dissipation plays a key role in the mechanism, turning the phase between horizontal and vertical particle velocities away from quadrature, allowing their product to have a nonzero mean. A by-product of this model is the result for the vertical structure of the surface waves (different from the classical potential–flow profile for uniform waves).

The models referred to above are based on the assumption of quasi-uniform waves (WKB- or geometric-optics approximation), which is valid for wave lengths small compared to the length scale of the horizontal ambient field (depth, current) variations. For smaller-scale problems, this may not be appropriate, in which case the WKB-approximation fails. Higher-order spatial derivatives (diffraction terms) can be taken into account in principle, as in the archetypical Airy-function solution for waves on a caustic including a blocking point. Phase-resolving wave models that allow a non-uniform (background) current are a more general alternative, although at enhanced computing costs. These could be Boussinesq models (2D), a non-hydrostatic shallow-water equation model as developed by Casulli/Stelling/Zijlema (2½D) or even a VOF-type model (3D). Note that the two last-mentioned classes of models also allow currents with arbitrary vertical shear.

2.7. Surf beat

The name "surf beat" was coined by Munk, who first reported observations of these waves. Today it refers collectively to various low-frequency waves in the nearshore region at the beat frequencies of the shorter incident wind-generated waves, encompassing both bound and free components. These may be incident waves, free modes that radiate from the nearshore zone to deeper water ("leaky modes") or free or forced waves that are refractively trapped in the coastal region, either at the water's edge ("edge waves") or at a shore-parallel bar ("bar-trapped waves") acting as wave guide. Another common name is "infragravity waves", suggesting that their frequencies are below those of gravity waves. This is in fact not the case since all these waves are controlled by gravity as the restoring force. Here the name "subharmonic waves" is used.

The study of subharmonic waves has received much attention in recent years, which has yielded significant progress in the understanding of their dynamics and in their modelling as well as insight in their relevance to coastal morphology.

Elgar et al. (1992) and Herbers et al. (1994) applied bispectral analysis to separate the total low-frequency wave field in bound and free components. They find that the relative contribution of bound energy increases with increasing incident short-wave energy. This is consistent with the picture of high-energy events of forced waves accompanying high-energy short waves against a background of weak free long-wave energy from unknown remote sources.

It has been known for quite some time that long waves accompany groupy incident wind waves and swell as bound waves (Biésel, 1952; Longuet-Higgins and Stewart, 1962). These are enhanced upon shoaling and are (partially) reflected as free waves. Also, free long waves can be generated and radiated both shoreward and seaward at the time-varying breakpoint of the incident short waves (Symonds et al., 1984). The former mechanism is dominant on gentle slopes and the latter on steep slopes, as measured by their contribution to the total energy of low-frequency cross-shore modes in the nearshore zone.

In the context of subharmonic waves on a beach, Battjes et al. (2004) distinguish the so-called mild-slope and steep-slope regimes, corresponding to low values (less than about 0.3) and high values (more than about 1) of a normalised bed slope parameter defined by $\beta = (h_x/\omega)\sqrt{g/h}$, in which h_x is the bed slope, ω the subharmonic frequency, h a characteristic depth in the shoaling zone and g the gravitational acceleration. Except for the replacement of wave height by water depth, this parameter corresponds to the surf-similarity parameter or Iribarren number that is commonly used to characterise the action of (high-frequency) wind-waves on a slope (Battjes, 1974).

In the mild-slope regime, the incident bound waves are found to have significant amplitude growth as they shoal, surpassing that of free waves. This is due to a net energy transfer from the grouped short waves to the accompanying long waves, owing to a phase lag of the group-induced long wave behind the envelope of the incident short-wave groups that develops as the waves shoal over the sloping bottom (Janssen et al., 2003). Moreover, in the mild-slope regime, the breakpoint moves over a relatively large distance, making this mechanism of generation ineffective due to phase cancellation (Symonds et al., 1984). This explains the dominance of the enhanced bound waves over the breakpoint-generated waves in the mild-slope regime. In the steep-slope regime, the aforementioned phase lag does not develop, or only weakly, for which reason the incident bound waves shoal very nearly with their energy conserved, i.e. according to Green's law for free waves, resulting in a relatively weak amplitude growth. Van Dongeren et al. (2004) fitted a power law to observed and computed variations of the amplitude (a) of incident subharmonic waves with depth in the shoaling zone ($a \sim h^{-\alpha}$) and found a strong correlation between the shoaling exponent (α) with the normalised bed slope β_b (where the subscript b designates the insertion of the breaker depth h_b in the expression for β). Fig. 4 shows that for large values of the latter parameter (steep slope regime) α tends to the value of 1/4, i.e. Green's law for conservative long-wave shoaling, and that it approaches the value 5/2, i.e. the equilibrium value in shallow water according to Longuet-Higgins and Stewart (1962), as β_b approaches zero, i.e. in the mild-slope regime.

Another characteristic difference between the two regimes is the degree of reflection. This is relatively high in the steep-slope regime and relatively low in the mild-slope regime. The transition range of the normalised slope parameter appears to be the same as that of the surf similarity parameter or Iribarren number, where the latter separates breaking from non-breaking of wind waves on a slope. This suggests that the low reflection of subharmonic waves in the mild-slope regime is due to breaking of these long waves (Battjes et al., 2004), rather than bed friction as has tentatively been suggested by Henderson and Bowen (2002). Analysis of laboratory observations supports this view, showing the same forward steepening of the long waves as they approach the shoreline, even to the same value, as for the primary, high-frequency waves (Van Dongeren et al., 2004).

Following Longuet-Higgins and Stewart (1962), numerical models for simulation of subharmonic waves are commonly based on the classical shallow-water equations with forcing by radiation stress gradients varying with the short-wave groups (a special case of wave–current interaction, see above). List (1992) and Roelvink (1993) first utilised the energy balance of the shoaling and breaking random short waves to predict the cross-shore variation of the short-wave energy (and radiation stresses) on the scale of the wave groups, and applied the results as a forcing in the numerical calculation of subharmonic waves. This was extended to two dimensions by Reniers et al. (2002), who calculated the corresponding subharmonic response with a linear frequency domain model assuming shore-parallel uniformity, and found very good correspondence of the

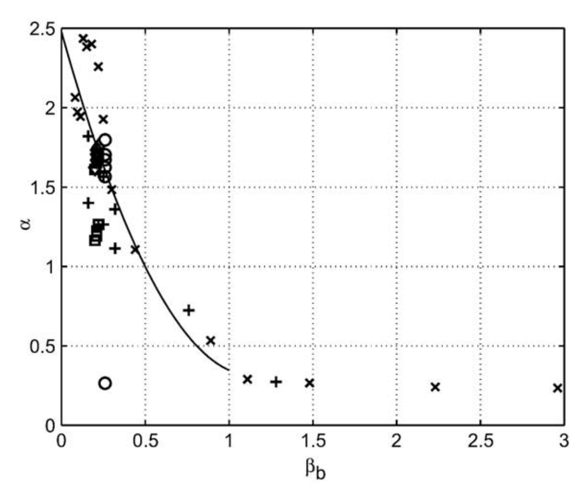

Fig. 4. Growth rate exponent α as a function of β_b. The figure is an ensemble of physical and numerical experiments in which the following parameter were varied: offshore depth (○), difference frequency (+), bed slope (×), shortwave modulation (□), shortwave amplitude (◊). The outlier in the lower left corner is for a case of very shallow offshore depth with hardly any shoaling. Source: Van Dongeren et al. (2004).

results with field observations at Duck. Van Dongeren et al. (2003) used the same short-wave driver to force the two-dimensional nonlinear time-domain model SHORECIRC. They too found good agreement of low-frequency spectra with the Duck data. An interesting item in their results is the evidence for bar-trapped waves in the data. To the author's knowledge, these works are the first to successfully predict the two-dimensional low-frequency nearshore wave field for arbitrary incident short-wave conditions. Needless to say, averaging the results over suitable time intervals yields the "steady" nearshore circulation on that time scale, which conventionally is computed assuming stationary conditions from the outset.

The modelling of wave-driven longshore currents has for decades been based on the idealisation of steadiness and alongshore uniformity (Bowen, 1969; Longuet-Higgins, 1970). Although this has elucidated the basic mechanisms involved, this approach also has severe limitations. One is that the resulting current was later found to be unstable, so that oscillatory vorticity perturbations develop (Oltman-Shay et al., 1989), frequently but incorrectly referred to as "shear waves." Secondly, even weak alongshore gradients of the mean water surface elevation (thus, alongshore pressure gradients) were found to significantly affect the resultant current velocity profile (Putrevu et al., 1995), typically causing the maximum velocity to occur in the trough, a region of weak if not minimal energy dissipation, as opposed to the alongshore-uniform results which put the maximum velocity invariably in regions of maximum dissipation, i.e. near the crest of bars and near the water's edge. Whereas both phenomena at some time were seen as corrections to the steady, uniform longshore current, now the situation has in principle been reversed: computations with group-scale forcing, as described above, resolve both effects and yield mean circulation patterns and velocities afterwards through averaging.

The numerical simulation of group-varying short-wave energy and the induced free and bound subharmonic waves in two dimensions also allows the simulation of harbour responses induced by these waves (Wu and Liu, 1990; Van Giffen et al., 2003), a possibility first mentioned and elaborated by Bowers (1977). In conjunction with a suitably modified sediment transport formula, it also allows the evaluation of the role of these low-frequency waves in coastal morphodynamics.

3. Morphodynamic processes and modelling

The area of most active research in the field of coastal sediment problems in recent years and at present is that of the so-called morphodynamics, i.e. the modelling of the processes determining the coupled evolution of sea bed topography and the wave–current field.

A striking feature of the nearshore morphological response to the forcing by waves and currents is the apparently spontaneous occurrence of rhythmical patterns in the sea bed elevation and the coastline, including virtually periodic beach cusps, crescentic bars, oblique bars and shore parallel bars with rip channels at more or less regular intervals, typically a few times the surf zone width, and, on a larger scale, spits and capes, in some cases several in a sequence. It has long been questioned whether these rhythmic patterns are the result of a corresponding forcing or the result of self-organisation, through an instability mechanism. Basically, one can distinguish two different approaches to investigate this question and to come to predictive models, the so-called reductionist (bottom-up) approach and the holistic approach. The former starts at the lowest resolved scale and synthesises these results through time integration on the assumption that this will lead to realistic predictions at much larger scales. The second identifies process variables that are dominant on the (larger) scale considered, and formulates (postulates) their interrelations. Whereas in the former approach the process time scale is much shorter than the scale of interest, these are the same in the latter approach.

At the smallest scale, the focus is on the quantification of the flow-induced sediment transport. These studies resolve the individual wave cycles, considering the instantaneous fluid motion and associated sediment pick-up and transport. Two recent contributions in this field are by Guizien et al. (2003), who consider the phases between the motions of fluid and sediment, and by Hoefel and Elgar (2003), who show the importance of including the (skewed) fluid acceleration in the formulation of sediment transport due to (nearly) breaking waves. Using measured fluid velocities as input, they were able to realistically simulate the cross-shore motion of a shore-parallel bar over a time interval of up to 45 days.

At the next higher scale, the sediment transport averaged over individual wave cycles is considered. This is used in practice to simulate coastal evolution, e.g. to "predict" effects of engineering structures, dredging, nourishment, etc. Models of this class have also been used for a scientific purpose, i.e. as a tool in short-term stability analyses of the coastal system, in which the system state is described through coupled evolution equations for the sea bed and the hydrodynamics. An initial state of alongshore uniformity is allowed to respond to random, infinitesimally small perturbations in bed level and/or in the wave/current field. Through a feedback between bed elevation and wave/current field, some alongshore modes are preferentially amplified to become eventually dominant. Hino (1974) gave a pioneering contribution along these lines. More recent results have been presented by Falqués et al. (1996), Deigaard et al. (1999), and Damgaard et al. (2002). Dodd et al. (2004) present a review of this category of stability models applied to sea bed and coastal morhodynamics. Reniers et al. (2000, 2004) have developed a model that fits also in this category, but they resolve the scale of the short-wave groups, whereas the other works average over the wave groups. We return to this model in some detail below.

Continuing upscale we come across bed evolution over a whole season, a year, decades, etc., and the associated larger-scale coastal features that evolve only slowly in time. Despite the remarkable recent successes of the reductionist approach, and the insights achieved in this manner, its usefulness for this class of problems is inherently limited. From a practical point of view, it becomes computationally prohibitive at long time scales. However, that might be surmountable. There are two more fundamental factors that limit its prediction horizon, i.e. the unknown effects of cumulation of model errors and the effects of feedbacks between the larger-scale response and the small-scale processes. An example of this is nonlinear localisation. This may upset the a priori assumptions of smoothness made in the small-scale modelling. How to deal with these problems is likely to remain a key challenge in coastal engineering research in the coming years.

Hanson et al. (2003) present an overview of coastal evolution models aimed at the yearly to decadal time scales. They distinguish models based on an assumed morphological quasi-equilibrium under the given external forcing (so reducing the degrees of freedom of the problem) and models in which this assumption is relaxed.

The EU-funded PACE-project (Prediction of Aggregated Coastal Evolution) was specifically aimed at the development of concepts and tools suitable for the medium- and long-term, up to millenia (see De Vriend (2003) and companion papers in the same volume). In this context, the notion of the so-called coastal tract has been introduced by Cowell et al. (2003a), who present a unified view of the upper shoreface, the lower shoreface (including the continental shelf) and the backbarrier (where present). Applications of this concept are presented in Cowell et al. (2003b).

As stated above, a holistic approach aims its modelling concepts at the larger scales of interest from the outset. It ignores details of the smaller-scale processes and tries to formulate phenomenological relations on the larger scale. Self-organisation under external forcing is the key notion here. With this approach, various (dry land) geomorphological features have successfully been explained, assuming only a feedback between processes and some kind of dissipation in the system (Kessler and Werner, 2003). It is believed to be a very promising avenue also for coastal research. A generic description of this approach has been given by Werner (2003).

Two recent examples of the holistic approach in the domain of coastal morphology are Ashton et al. (2001), who explain the occurrence of large-scale coastline features as spits and capes, and Coco et al. (2003), who present a self-organising model for beach cusp formation (doing away with the more conventional notion of edge wave forcing as the causative process). In this connection, we can also mention Van Goor et al. (2003), who deal with the impact of sea-level rise on the morphology of tidal inlets. This does not involve rhythmic patterns as a result of self-organisation, but there is a parallelism in the use of only macroprocess variables and their interrelations, instead of a bottom-up approach starting at the scale of instantaneous, local sediment transport rates. The same applies to the so-called Bruun rule for the estimation of the rate of shoreline regression due to sea level rise (Bruun, 1962). It is based on the notion of an equilibrium beach profile, considering cross-shore motions only. Alongshore variations can also play a role, particularly adjacent to estuaries and tidal inlets. These can even change the sign of the response (Stive, 2004).

Following the preceding discussion, we conclude this paragraph with references to some recent work on morphodynamic modelling on the cross-shore scale of the surf zone, including the prediction of rhythmic patterns, using a bottom-up approach. Realistic numerical simulation of these patterns along these lines on the time scale of several days has become possible only recently.

The appearance of an alongshore periodic bed response has generally been taken to imply the existence of steady patterns in the hydrodynamic forcing with alongshore periodicities. The occurrence of obliquely incident wave fields with the same frequency from two different sides of the shore normal is one possibility (Dalrymple, 1975). Standing edge waves and the associated induced streaming is another. Holman and Bowen (1982) describe a number of morphological patterns that could arise as a result of different combinations of phase locked edge waves. However, a proof-linking an observed bed level response with alongshore periodicity to a corresponding identified hydrodynamic forcing is missing. Nevertheless, because the observed bed features are typically much longer than the incident short waves, it has long been suspected that the subharmonic (infragravity) waves play a key role in the generation of these features.

As was mentioned above in the context of surf beat, it is now possible to numerically simulate the two-dimensional subharmonic waves due to arbitrary incident random short waves propagating and breaking over arbitrary (but mildly sloping) topography. This has enabled the development of a coupled model for the hydro/morphodynamics which turned out to be capable of reproducing the growth of remarkably realistic, quasi-periodic bed features consisting of an alongshore bar with a system of rip channels on an initially plane beach (Reniers et al., 2000). To achieve this result, it has been found essential to resolve the wave groups. This has initially been taken as confirmation that the group-induced gravity waves (surf beat of one kind or another) indeed is essential in the formation of these rhythmic bed features.

In a more recent contribution, Reniers et al. (2004) have used this hydro/morphodynamic model as a tool to specifically address the question referred to above: is the bed response forced or free (self-organising)? Remarkably, they find that the subharmonic *wave* motion is not essential to the development of rhythmic patterns. Instead, it is the *vorticity* that is injected in the nearshore waters through the gradients of the group-varying short-wave energy dissipation due to breaking (Peregrine, 1998), which gives rise to circulation cells that can persist much longer than the wave (groups) that triggered them. According to these results, an initial state of alongshore uniformity, subject to groupy incident short, breaking waves, develops into a set of circulation cells (Fig. 5) whose spacing is dictated by the alongshore variation of the group structure of the incident short waves.

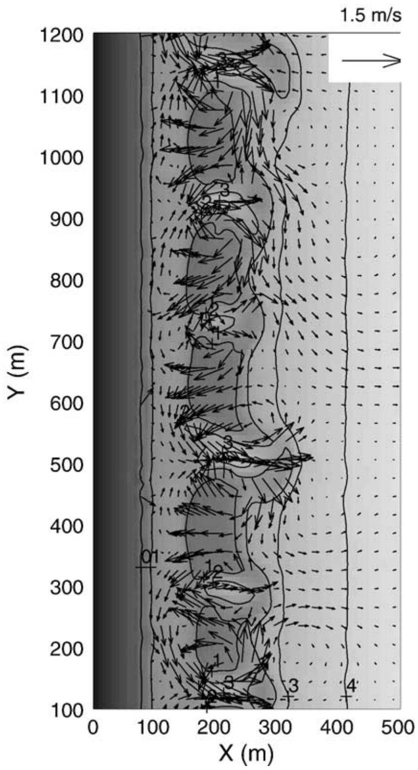

Fig. 5. Computed bed elevation (depths indicated by grey scale and by depth contours at 1-m intervals) and 15-min averaged, depth-averaged velocity (arrows) due to short-crested, random, normally incident (in the mean) waves with peak period = 10 s, rms wave height = 1.0 m. A system of rip channels has developed in the sandy beach that was initially uniform alongshore, weakly concave and with a single bar. Evolution shown is after 90 h; computations were done in a domain with reflecting lateral boundaries 1480 m apart, but the plot shows only an 1100-m-long stretch. Figure adapted from Reniers et al. (2004) (courtesy Ad Reniers).

So, this initial disturbance is forced. The location of the initial, forced pattern arises randomly. However, from then on, the positive feedback between bed formation and flow (deeper parts attracting more discharge) takes over, as in the instability of a self-organising system. In the author's opinion, this work is a breakthrough in our thinking about the dominant processes in the nearshore hydro/morphodynamics. It deserves follow-up studies to scrutinise and further elaborate the results.

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