Journal of Coastal Research	SI 39	21 - 27	ICS 2004 (Proceedings)	Brazil	ISSN 0749-0208

Abstracted Modelling as a Tool for Understanding and Predicting Coastal Morphodynamics

D. A Huntley†; G. Coco‡ and T. J. O'Hare†

†School of Earth, Ocean and Environmental Sciences, University of Plymouth, Plymouth, Devon, PL4 8AA, U.K.
dhuntley@plymouth.ac.uk
tohare@plymouth.ac.uk

‡National Institute of Water and Atmospheric Research, P.O. Box 11-115, Hamilton, New Zealand.
g.coco@niwa.co.nz

ABSTRACT

HUNTLEY, D. A.; COCO, G. and O'HARE, T. J., 2006. Abstracted modelling as a tool for understanding and predicting coastal morphodynamics. Journal of Coastal Research, SI 39 (Proceedings of the 8th International Coastal Symposium), 21 - 27. Itajaí, SC, Brazil, ISSN 0749-0208.

Understanding and predicting the morphodynamic behaviour of coastal features such as ripples, cusps and bars remain major challenges for coastal scientists and managers. One approach which is becoming more widely used is the development of 'abstracted' models, in which the processes driving the dynamics of the coastal system are described through a minimum number of variables and interactions which encapsulate non-linear feedbacks between hydrodynamic forcing and sediment response. In this paper we review examples of such models for coastal ripples, beach cusps and large-scale coastal bars. In each case, highly simplified abstractions of physical processes produce quasi-regular morphological features which are in remarkable agreement with observations, most notably in length scales and two-dimensional form. In the case of cusps the agreement has been shown to extend to quantitatively correct limits on conditions for the growth and suppression of the features. We conclude that abstracted models have considerable value in comparison with more 'traditional' modeling approaches. They provide indications of the essential minimum physical processes responsible for observed features. They also make direct use of stochastic forcing to provide time-domain simulation of the development of coastal morphology to finite amplitude and quasi-equilibrium forms. Their simplicity holds the promise of being able to study the statistical behaviour of coastal systems under a variety of forcing scenarios.

ADDITIONAL INDEX WORDS: *Beach cusps, ripples, nearshore bars, morphodynamics, self-organization.*

INTRODUCTION

The concept of a beach as an essentially straight junction between the sea and the shore, with depth increasing monotonically seawards, is rarely borne out in practice. Beaches generally display a wide range of variations alongshore and will also often possess offshore bars which create shoals at a distance from the shoreline. In many cases the alongshore variations have a remarkable degree of regularity, so that a distinct alongshore wavelength can be defined. At a small scale, beach cusps, with alongshore scalloping repeated every few metres, are frequently found on beaches which are otherwise featureless. Larger scale features which extend across and beyond the surf zone include shoreface-connected ridges and crescentic bars, the latter often mirrored by mega-cusps along the shoreline. In trying to explain the existence of such regular features much effort has been placed on developing links to long period wave motion which can have alongshore wavelengths and cross-shore structures of the same scale as these features. The basic hypothesis in these studies is that the regular morphological features are forced by pre-existing hydrodynamic motion at the scale of the features. This hypothesis has had a number of notable successes. It is now well recognised that long period hydrodynamic motion of the required scales, in the form of edge waves, indeed exists on many beaches where appropriate morphological features are found (eg HUNTLEY *et al.*, 1981). The form of edge waves has also been shown to be similar to the detailed shapes of a number of observed morphological features (HOLMAN and BOWEN, 1982).

However there are several unsatisfactory aspects of the hypothesis that regular hydrodynamic motion is required to create regular morphodynamic features. The most obvious problem is that the long period hydrodynamic motion observed on natural beaches is generally found to span a broad band of 'infragravity' frequencies (typically 0.05 - 0.005 Hz). Whilst spectra of nearshore motion measured at a given distance from the shoreline do show peaks and troughs in the infragravity band, these can generally be explained in terms of the offshore locations of the nodes and antinodes of a broad-band spectrum of cross-shore-standing waves (eg GUZA and THORNTON, 1985; RUESSINK *et al.,* 1998; HOLLAND and HOLMAN, 1999). The dispersion relation for edge waves clearly shows that a broad frequency range of this kind must be associated with a broad range of alongshore length scales and so cannot readily be linked to the prominence of a single length scale such as is seen in regular morphodynamic features. A small number of field observations do suggest that some form of preferential excitation of particular frequencies may occur in some circumstances. AAGAARD and BRYAN (2003) show spectra of currents from a beach on the Danish coast which they interpret as demonstrating resonant excitation of long period motion linked to the distance between the shoreline and an offshore sand bar. Laboratory measurements by BALDOCK *et al.* (2004) using random waves propagating over a barred beach, and some theoretical work (SYMONDS and BOWEN, 1984), support the suggestion that frequency selection may occur in this way. However it is clear that such selection requires the pre-existence of a bar at a given distance offshore, a feature whose existence we would also like to explain. A further problem with the long wave hypothesis is that recent detailed observations seem to indicate the appearance of rhythmic patterns in the morphology in the absence of edge waves (HOLMAN and HOLMAN, 1996) or while the infragravity band variance was observed to decline (HOLMAN and SALLENGER, 1993). Finally, the edge wave approach neglects the feedback of the evolving bathymetry on the hydrodynamics despite the fact that such interactions occur in a highly nonlinear and dissipative environment.

These problems with the long-period hydrodynamic hypothesis highlight the more general problem: how do regular features, whether morphodynamic or hydrodynamic, develop from stochastic, broad-band, forcing by incident waves on natural beaches? A possible answer to this question is found by considering the hydrodynamics and sediment dynamics of the nearshore environment as components of a single coupled system, in which the changing topography due to sediment transport feeds back non-linearly to modify the hydrodynamics. The emerging morphology is then the result of this non-linear coupled system. The developing understanding of such nonlinear coupled systems shows that they may exhibit a range of behaviours depending upon the degree of nonlinearity and the forcing (eg SOUTHGATE and MÖLLER, 2000). In some circumstances free regular features can emerge by a process known as 'self-organisation' without the need for matching regularity in the forcing. The hypothesis is that regular coastal features are examples of such free, self-organising regularity.

Recent research modelling the non-linear coupling between hydrodynamics and topography has developed a 'spectrum' of approaches. At one end of the spectrum, which we might call the 'traditional' end, there are linear and non-linear analyses of the basic physical equations describing the hydrodynamics, sediment transport and bed-level changes. Linear analyses reveal the scales of developing morphology that are likely to grow from small perturbations from a basic state (eg FALQUES *et al.* , 2000). Fully non-linear analyses allow topographic features to grow to finite size and so reveal what might be the final form of such features (which may not be the same as the initially fastest-growing) (eg CABALLERIA *et al.*, 2002). At the other end of the 'spectrum', which we might call the 'radical' end, are the so-called 'abstracted' models (WERNER, 2003), where the processes driving the dynamics of a physical system are described through a minimum number of variables and interactions which encapsulate a non-linear positive feedback which allows features to grow and some form of negative feedback which limits the growth of such features. Such abstracted models are sometimes developed using the 'cellular automata' framework but, in such cases, perhaps a better description is 'discrete agent' models since typically the physical system is modelled as a set of discrete units or agents which behave according to the defined abstractions of physical processes. WERNER (1999, 2003) has suggested that these abstracted models should be developed as a hierarchy in which the description of the dynamics at one level of detail should be defined independently of the abstractions for slower and faster scales. For example WERNER and KOCUREK (1999) model the form of a field of aeolian ripples by defining a set of abstractions governing the bifurcations of ripple crests, independent of traditional sediment transport formulae. Other abstracted models move slightly away from the extreme of this 'spectrum' by using numerical techniques closer to the 'traditional' solution of partial differential equations and defining abstractions as simplified forms of the physical understanding of faster scale processes.

This paper aims to review some of the abstracted models which have been used to describe nearshore morphology. Whilst these abstracted models are undoubtedly highly simplified representations of reality, we plan to show that they have a number of features which make them very valuable in investigating the origins and behaviour of coastal morphology.

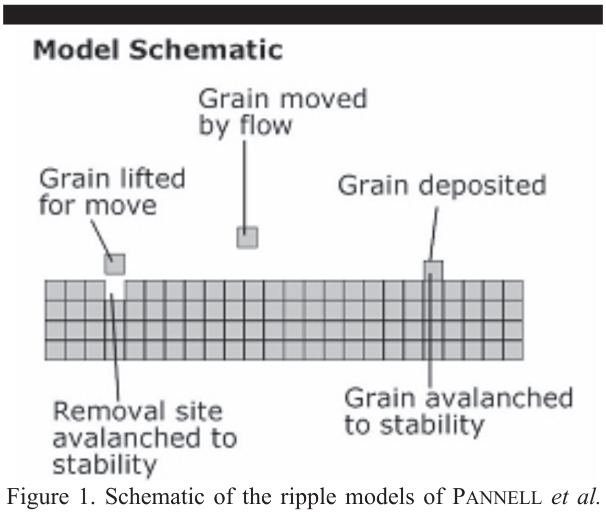

Figure 1. Schematic of the ripple models of PANNELL *et al.* (2003).

Such modelling is still in its infancy but shows remarkable promise for explaining many features of nearshore behaviour which are not readily explained by other modelling approaches.

In the following three sections abstracted models for three different types of coastal morphology are described, first, at the smallest scale, ripples, then beach cusps and finally features with spatial scales of kilometres and timescales of decades. We then draw some general conclusions about the potential and limitations of such models for modelling and predicting coastal morphodynamics.

COASTAL RIPPLES

Models of aeolean ripples were amongst the first abstracted models for natural morphological features (NISHIMORI and OUCHI, 1993; LANDRY and WERNER, 1994; OUCHI and NISHIMORI, 1995). More recently, PANNELL *et al.* (2003) have presented a model for marine ripples which includes a study of the influence of oscillatory flow and combined oscillatory and steady flows.

The model of PANNELL *et al.* (2003) considers the motion of individual grains of sand within a domain of sufficient length to encompass a significant number of ripple wavelengths (typically thousands of grains) and, when 2D effects are studied, sufficiently wide to enable bifurcations of ripple crests to be encompassed (typically hundreds of grains). The model requires on the order of 10^8 grain motions to be undertaken within such a domain for ripples to develop. To make such a model run within a reasonable time it is therefore necessary to define simple rules governing the motion of each grain. PANNELL *et al.* (2003) describe two such sets of models. For both models the basic process is shown in figure 1. A grain is randomly chosen from within the domain and moved downstream a distance determined by the rules applied. At both the original and final locations of the grain avalaching is then allowed to take place, to represent the effect of a maximum angle of repose. Grains leaving the model domain at the downstream end are reintroduced at the upstream end. Tests were made to ensure that this boundary condition did not influence the scale or rate of ripple development.

In the first model the distance moved by each grain is a simple function of the flow speed and the relative height of the grain above or below the mean bed level. Grains move further when the flow speed increases and/or when the grain originates from higher above the mean bed. In the second model a more 'realistic' set of abstractions is used, in which grains are given a starting 'energy' based upon the flow speed and elevation, and then lose that energy in differing amounts depending upon the form of the bed they are moving over. For example energy is lost more rapidly over the lee side of emerging topography than the stoss side, to simulate the effect of sheltering in the lee. In order to run efficiently this model was restricted to a domain only a single grain diameter wide, thus only enabling a study of the development of longitudinal ripple wavelengths. Other models intermediate in complexity have also been run, including some in 2D, in order to compare results with those obtained using the simplest model.

Figure 2 shows a typical plan view of an emerging ripple field using the simpler model of PANNELL et al. (2003). Immediately striking is the qualitatively realistic shape of the

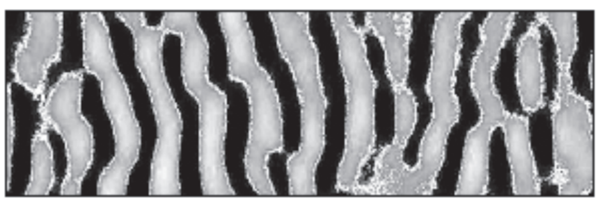

Figure 2. Plan view of ripple geometry created by the first PANNELL *et al.* (2003) model. Dark shades represent ripple crests and light shades ripple troughs. The flow was from left to right.

ripple crest lines, with long-crested transverse crests exhibiting a degree of sinuosity and broken by bifurcations. Quantitively the wavelengths of these emerging ripples are around 400 grain diameters and the ratio of wavelength to height is of the order of 7, both features in good agreement with natural ripples. Similar qualitative and quantitative agreement was found for the more complex 'energy' model. However the fact that the simple model is sufficient to reproduce these features suggests that ripple formation only requires that grain movement depends upon elevation and flow speed.

With increasing flow speed, the model shows increasing bifurcation of ripple crests and eventually at very high flows the bed develops large irregular regions of mounds and hollows. Again this behaviour is consistent with observations (ALLEN, 1984). A possible explanation for this behaviour arises from consideration of the model abstractions. The only transverse process included in the model is the avalanching which occurs at the initial and final locations of moving grains. A very simple representation of avalanching is used, in which grains were chosen for avalanching if they stood higher than n grains above their neighbours (where n could be varied), and the avanching grain was moved in a random direction until it no longer fulfilled the avalanche condition. Avalanching was found to be essential for the formation of realistic ripples but the form of the emerging ripples was found to be insensitive to the precise rules. However an important aspect of this avalanching is that it is independent of the flow speed. Thus at low flow speeds it is relatively more important in the formation of the bed morphology than at high flow speeds, when longitudinal grain translation dominates. Thus transverse along-crest coherence of the ripple field is expected to be more significant at low flow speeds than at high flow speeds, in agreement with the observations.

Modelled rates of ripple formation and down-stream migration rates are also found to be in good agreement with observations. Ripples in nature and in the model are found to develop from irregularities in the bed with shorter, smaller-scale features migrating faster and merging into larger scale features. A controversial aspect of ripple development is whether they reach an equilibrium wavelength or continue to grow in scale at an increasingly slow rate as the scale increases. Some laboratory observations suggest that 'mode-changes' in ripple spacing occur between periods of relative stability (STEGNER and WESFRIED, 1999). Such changes are observed in the model also, but it is still unclear whether they are controlled by the limited longitudinal domains of both the models and the laboratory experiments. Nevertheless the model results do appear to support the suggestion that ripple spacing may reach a quasi-equilibrium relatively quickly but will continue to grow over time at a rate which decreases dramatically as the scale increases.

The 'energy' model of PANNELL *et al.* (2003) was also used to study the development of ripples in time-varying flows, with similarly encouraging results when compared to observations.

One feature of current ripples not yet reproduced by the model of PANNELL *et al.* (2003) is their observed asymmetry, with a steep down-stream lee slope and shallow upstream stoss slope. Work is continuing in order to discover how to reproduce this defining property of current ripples.

The important conclusion from these models is that, with the possible exception of the asymmetric profile, the observed features of natural marine current and wave ripples are reproduced both qualitatively and quantitatively by a model in which the physical processes are reduced to a few very simple rules. Furthermore the models are able to simulate the inherent randomness of the three-dimensional form of finite amplitude ripples and their development over long periods, aspects which more traditional approaches would find much more difficult or impossible to reproduce.

BEACH CUSPS

In their seminal paper, WERNER and FINK (1993) described an abstracted model for the development of beach cusps (Figure 3) within the swash zone of a sloping beach. Further work by COCO *et al.* (1999; 2000; 2001; 2003a, 2003b) studied the sensitivity of such a model to the nature of the abstractions, and compared in detail the behaviour of modelled and observed cusps.

Figure 4 shows typical cuspate morphology developed after a number of swash cycles. As shown by WERNER and FINK (1993) the wavelength of these cusps is related to the cross-shore length of the swash excursion. COCO *et al.* (1999) confirm that the predicted wavelengths are consistent with observations. Interestingly, they also show that, under the reasonable assumption that the natural period of swash motion up and down a slope is equal to the period of incoming waves ('saturation' of swash flow), this relationship between cusp wavelength and swash excursion is equivalent to the previously-postulated relationship linking beach cusps with subharmonic edge waves. The unfortunate conclusion is that the edge wave hypothesis and the mechanism captured by the abstracted model cannot be distinguished from each other on this basis. However, COCO *et al.* (2000; 2003a, 2003b) show that the abstracted model is able to reproduce a number of other observed features of naturally occurring cusps. For example, the natural deviations from exact regularity are qualitatively well reproduced by the model. Figure 4 shows the locations of cusps for three runs which differ only in the random seed used to choose the initial velocities of the moving agents. As expected the locations of crests and troughs is random, but it is also clear that the spacing and relief of the cusps has a randomness superimposed on an underlying regularity, as observed in natural conditions.

Another feature of observed beach cusps which is quantitatively well reproduced by the model is their sensitivity to the angle of wave incidence. Figure 5 shows model results

Figure 3. Beach cusps at Tairua Beach (New Zealand).

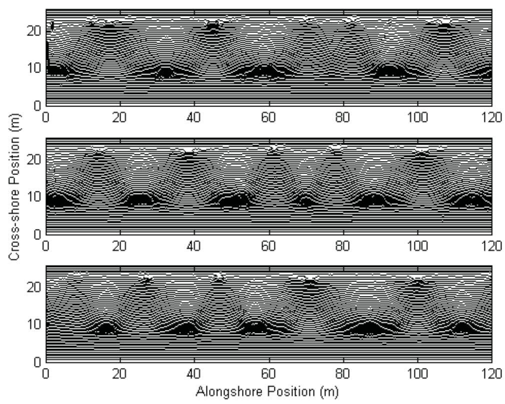

Figure 4. Beach cusp formation. Each subplot represents a different simulation after 200 swash cycles. Forcing conditions only differ in the seed used in the random number generator. Initial beach slope = 6°, average swash excursion = 12m.

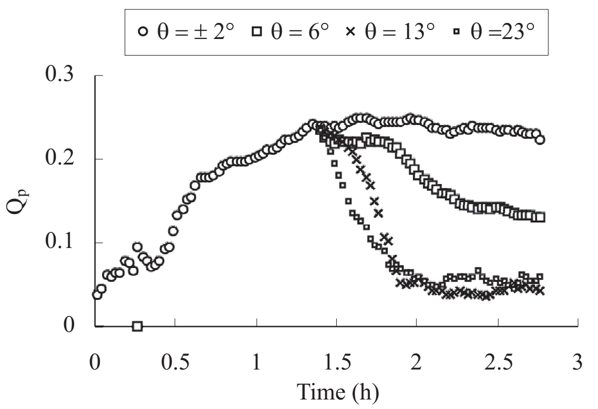

Figure 5. Variation of peakedness factor (evaluated over an alongshore transect of bed elevations) for different angles of beach cusp approach. The vertical axis is a measure of the Q-factor of the peak in the spectrum of elevation along an alongshore line at the centre of the cusp field. A value of around 0.22 represents a well-developed cusp field whilst values of less than about 0.1 show no noticable cusp features.

where cusps are allowed to form to a quasi-equilibrium form under normally incident waves and are then subjected to waves of varying incidence angle, simulated by adding a mean alongshore velocity to the initial motion of the agents. For an incidence angle of 6° cusps become more variable in position and spacing, and for angles of 13° or more are wiped out. These model predictions are consistent with, for example, the detailed observations of HOLLAND (1998), where all but one cusp formation event occurred for breaker angles within 12° of shore normal.

Beach cusps are also generally found to occur only when the incident wave field is relatively narrow banded (INMAN and GUZA, 1982; HOLLAND, 1998). The cusp model does not inherently consider the frequency of swash motion since each swash cycle is initiated independently. However, as previously mentioned, it is reasonable to link the natural period of a single swash cycle to the period of incident waves. We can therefore simulate the effect of increasing the range of incident wave periods by increasing the degree of randomness imposed on the underlying upslope velocity given to the agents at the start of each cycle. A number of runs were therefore made using identical random seeds but varying the ratio of randomness to mean flow for the upslope velocities from 1% to 50%. The results are shown in Figure 6 where the number of swash cycles needed for cusps to grow to a quasi-equilibrium scale is plotted against the percentage randomness. These results show that cusp development is increasingly suppressed as the degree of randomness increases; beyond about 50% no cusps were observed. Thus again the model results are in good qualitative agreement with observed cusp behaviour. Further work is in progress to try to quantify this effect.

COCO *et al.* (2003a) also show that detailed predictions of the way in which cusps develop from an initially plane beachface are in good agreement with field observations. Their field

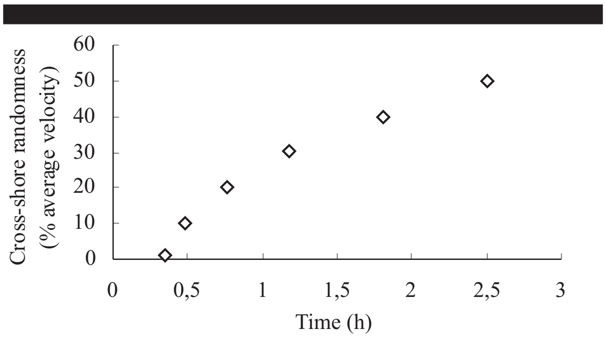

Figure 6. Randomness in swash excursion and time needed for beach cusp formation.

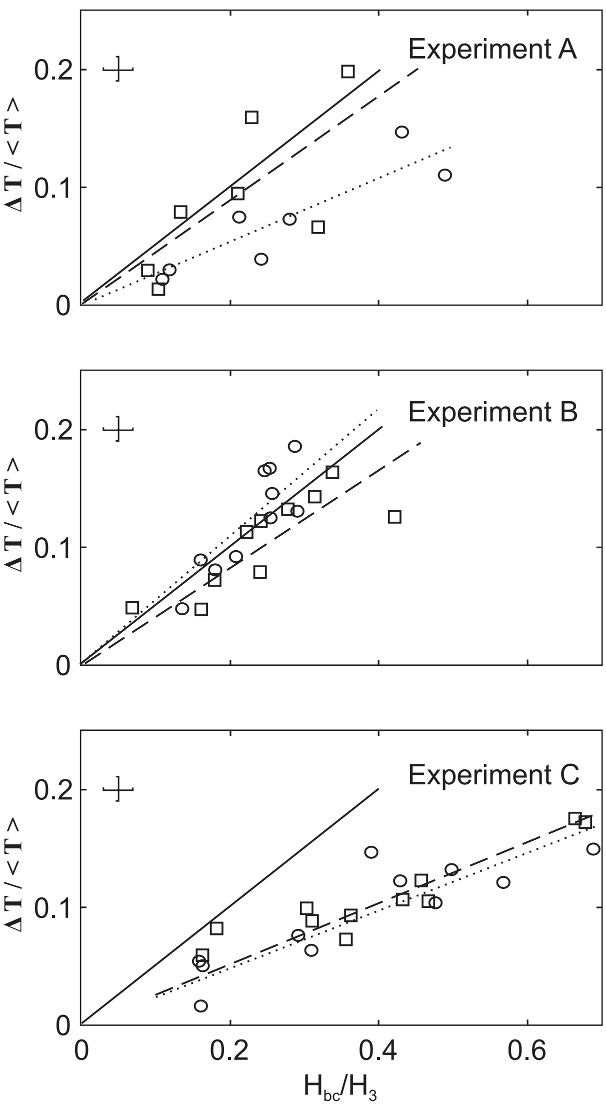

Figure 7. Normalized bay-to-horn time lag versus normalized beach cusp height for field measurments (circles) and numerical simulations (squares) for 3 experiments conducted at Duck (NC, USA). Solid line is theoretical prediction, and the dotted and dashed lines are field and numerical model best fit regressions, respectively. Statistical uncertainties (upper left corner) are estimated to be 0.02 for the beach cusp height parameter and 0.01 for dimensionless time lags. (Used with permisson of the American Geophysical Union, from COCO *et al*., 2003a, Journal of Geophysical Research, 108(C3), 3101, 46.8).

observations consisted of video measurement of swash front motions and high-resolution surveys at 3-4 hour intervals, on a beach initially smoothed by a bulldozer. A key signature of the model of cusp formation is the existence of positive feedback between the swash flow and the topography as cusps form. In particular the model predicts that the motion of the swash front in developing cusp bays lags behind the motion on cusp horns, and this time lag is expected initially to be a linear function of the relief of the cusps. Figure 7 shows plots of the normalised time lag against normalised cusp relief for three observed events and it is clear that observations and predictions are in very good agreement for the second and third events. The authors suggest that the more ambiguous results for the first event probably result from the existence of significant infragravity motion on that day coupled with limited spatial resolution of the surveys.

An interesting feature of the cusp model is that the rate of cusp growth varies widely depending upon the details of the random velocity components. Figure 8 shows four runs again differing

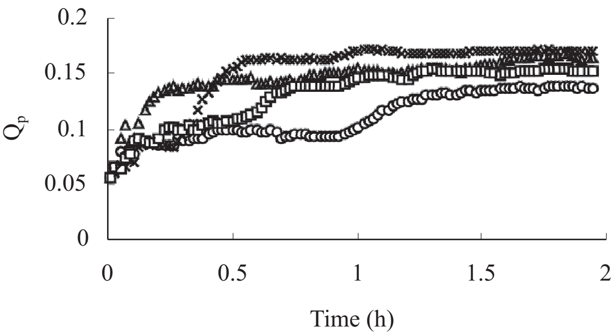

Figure 8.Cusp growth rate for four runs with different random seed in the forcing conditions.

only in the random seed used. It is clear from this figure that in one case (shown as triangles) cusps grew to a quasi-equilibrium state within a few minutes whilst in other cases the same prominance of the cusps took up to almost 1.5 hours. Once formed, the cusp field is also seen to be subject to continuing variations in prominance, often associated with relocation of the positions of horns and troughs along the beach. It is possible that this intrinsic variability is responsible for the observation that cusps frequently form in groups along a beach face, separated by stretches of planar beach without cusps, even where the exposure to incident waves appears to be identical. Where incident conditions vary too rapidly to encompass the full range of cusp growth rates, this 'patchiness' in the occurrence of cusps may be expected.

In summary, the abstracted model for beach cusps reproduces all of the observed behaviour it has yet been tested against, including length scales, relief, sensitivity to incident wave angle and spectral breadth, and feedback between swash flow and cusp relief. It is also remarkable that this agreement is generally insensitive to details of the model parameterisation. In particular, although the absolute rate of cusp formation depends upon the form of the sediment transport formula used, the qualitative features of developing and quasi-equilibrium cusps remain essentially unchanged if different formulations are used, provided of course that they involve a non-linear function of flow speed.

LARGE SCALE COASTAL MORPHOLOGY

Large scale coastal features such as crescentic bars, shoreface-connected ridges and offshore bars are of course of much more importance to coastal managers than beach cusps or sand ripples, but abstracted modelling of such features is to date very limited. Nevertheless ASHTON *et al.* (2001) describe an interesting model for features with alongshore spacing of kilometres and time scales of decades which we briefly review

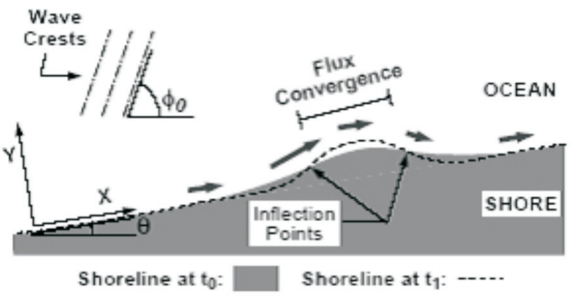

Figure 9.A schematic plan view of the instability mechanism of ASHTON *et al.* (2001). Waves approaching the shoreline at a highly oblique angle generate alongshore sediment fluxes shown by the heavy arrows, where the length of the arrow indicates the relative strength of the flux. The consequent zones of erosion and accretion reinforce shoreline perturbations. Reprinted by permission from Nature (vol 414, 296-300), copyright 2001. Macmillan Publishers Ltd.

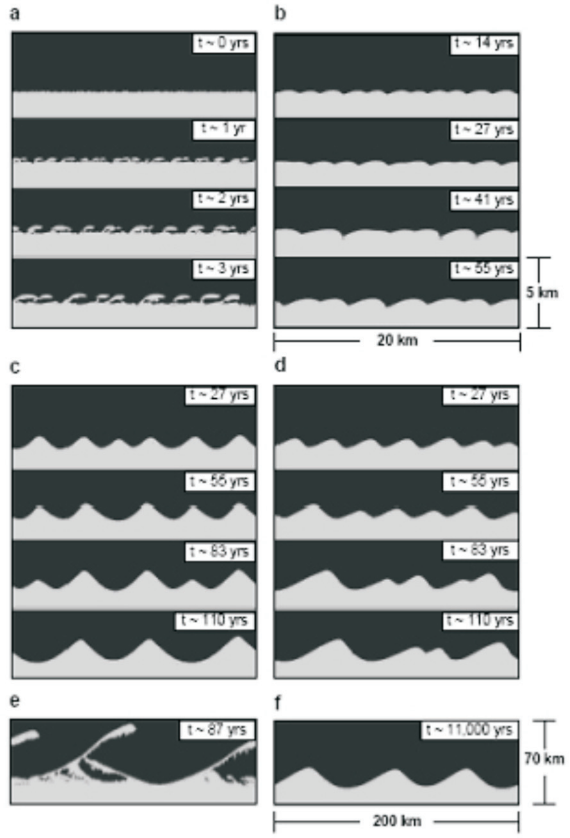

Figure 10. Plan view of the ASHTON *et al.* (2001) model domain showing shoreline evolution, a) for a single deep water wave angle of 55º, b) for a random distribution of wave angles weighted towards high angles and towards waves approaching from the left, c) as for case (b) but with waves symmetrically distributed from left and right, d) for slight asymmetry, e) longer term evolution of a cuspate spit, and f) an undular shoreline, using a cell width 10x larger than for a-d. Reprinted by permission from Nature (vol. 414, 296-300) Copyright 2001. Macmillan Publishers Ltd.

in this section.

The physical basis of the ASHTON *et al.* (2001) model is shown in figure 9. Waves approaching a shoreline at a high angle of incidence will drive an alongshore current and associated alongshore sediment transport. Since maximum transport is expected for a breaker angle of 45°, perturbations of shoreline orientation about this angle can create regions of sediment convergence and divergence, causing the perturbations to grow. ASHTON *et al.* (2001) model this positive feedback mechanism by dividing a plan view of the shoreline into cells and allowing sediment to move between the cells according to standard alongshore transport equations.

As with the ripple and cusp models, quasi-regular shoreline perturbations are found to emerge, though in this case on timescales of years and spatial scales of kilometres (figure 10). For waves from a constant angle the perturbations consist of narrow spits which extend seawards before turning downdrift and parallel to the shore (fig 10a). However more realistic simulations use directional spectra of incident waves and produce a range of undular and cuspate shorelines over periods of decades, with shapes which depend upon the directional spread (fig 10). The authors find that quasi-regular shoreline features grow for all directional distributions weighted towards high angle waves. As in the case of ripples (see WERNER and GILLESPIE, 1993), there is evidence that the alongshore scale of the perturbations continues to increase with time, but over increasingly long time scales. A similar process of scale increases occurs, with smaller perturbations moving more quickly and becoming incorporated into larger scale perturbations.

Comparisons with natural features are at present only descriptive but are nevertheless striking. ASHTON et al. (2001) show satellite images of shorelines in the Sea of Azov, Ukraine and along the Carolina coast of the USA where prominant wind directions are strongly alongshore and where shoreline undulations match modelled features in both scale and general form. Other comparisons have also been recently undertaken (ASHTON *et al.*, 2003).

The ASHTON *et al.* (2001) model deals with only one possible process for development of these largescale features, and omits a number of phenomema which might be relevant such as wave diffraction, wave height variations due to convergence on headlands and divergence in bays, tidal residual flows and variations in grain size. There is also a need to test the model in detail for particular observed features, using local wave climates and underlying topography. Nevertheless it is clear that once again a simple model can produce quasi-regular shoreline morphology which matches observed features remarkably well both qualitatively and quantitatively.

BENEFITS AND LIMITATIONS OF ABSTRACTED MODELS

In the context of the 'spectrum' of models described in the introduction, the models which have been reviewed here are towards the 'radical' end, though the abstractions are in each case based on well-defined physical priciples. An alternative approach is to use 'traditional' perturbation techniques which are based upon as complete an understanding of the fast-scale physical processes as possible. The question therefore arises as to the relative advantages and disadvantages of the abstracted approach. In this section we use the examples which have been reviewed to address this question, and try to draw some general conclusions about the applicability and value of such models to the understanding and prediction of coastal morphodynamics.

Perhaps the most striking feature of the models which have been reviewed is their ability to reproduce a wide range of observed characteristics of coastal morphology and morphodynamics from highly simplified descriptions of the underlying physical priciples. Thus realistic ripples develop from abstractions which ultimately simply require the distance moved by individual grains to depend in some way on flow speed and their original elevation above the mean bed level. Whilst other more complex formulations have been used, the basic results remain unchanged. For beach cusps most of the predicted features are insensitive to details of the sediment transport formulae used. For the larger scale features modelled by ASHTON *et al.* (2001) only a limited subset of refraction effects are included yet the model appears to simulate coastal morphology with remarkable accuracy.

One use for abstracted models might therefore be to explore and determine the underlying essential physical processes responsible for the observed features. Of course different characteristics of coastal features may depend upon different processes. It is clear for example that simulating the plan form of ripples requires only the simple elevation-based transport and an avalanching process to stabilise the bed. More complex physics might be required, however, to simulate the asymmetrical profile of current ripples.

Another feature of abstracted models is their direct use of stochastic forcing to provide time-domain simulations of the development of coastal morphology. The models also readily extend to finite amplitudes and simulate quasi-equilibrium forms, aspects which are difficult to reproduce using traditional non-linear perturbation models. The use of abstractions can also make the models quick to run on standard computers, allowing many realisations of a stocastic process to be simulated from which the statistics of the response can be assessed. Taking advantage of such rapid runs, work is currently in progress to assess the statistical distribution of cusp growth rates for different forcing scenarios. By comparison, multiple runs with most 'traditional' non-linear perturbation models are time-limited and consequently rare. The statistical behaviour of coastal systems under a variety of forcing scenarios is obviously of great interest to the long-term management of the coastal zone. It is likely that abstracted models will play an increasingly important role in this regard. Recent work (COCO *et al.*, 2003b) also seems to indicate that, once all the relevant processes have been included, abstracted models can also successfully predict detailed morphodynamic evolution over time scales significantly larger than other modelling approaches.

Perhaps the most important limitation of abstracted models relates to the lack of absolute guidance in selecting and formulating the abstractions of physical processes. Since they are generally removed from the direct application of standard physical equations, there is no guarantee that the abstractions which appear to be successful in simulating a morphodynamic feature are unique in their ability to do so. Other sets of rules might be equally successful. Of course even 'traditional' models may provide misleading results if simplified to the point of omitting zero-order effects. However, for these traditional models the simplification process is generally carried out in the context of an explicit set of equations and is often justified by a quantitative scaling argument. The process of simplification is therefore clear and controlled. In the case of abstracted models, on the other hand, the process of abstraction is not, in principle at least, constrained by a set of equations quantifying the range of possible physical processes. The choice of abstractions is essentially arbitrary and 'trial and error' are intrinsic to the process. The validity of such models must therefore depend heavily on their ability to simulate a wide range of observed behaviours. Indeed new sets of observations, for example comparisons of statistical behaviours, need to be sought to test the models.

A second problem is that the models can be sensitive to the discretisation used. For example growth rates in the cusp model are found to be linearly related to the number of discrete agents used. Hence absolute growth rates can only be estimated if the model can be calibrated in some way against observations. Again, this is not in principle different from traditional modelling; calibration of sediment transport models is vital in all cases. However it is important to recognise that traditional calibration techniques cannot be transferred to abstracted models. New calibration procedures are needed.

Nevertheless, despite these limitations, abstracted models show enormous promise for understanding and predicting coastal morphodynamics. It is now clear that non-linear interactions between hydrodynamics and sediment dynamics control many aspects of the development and behaviour of coastal morphology. Abstracted models provide the means by which these non-linear interactions can be efficiently studied and the statistical behaviour of the non-linear coastal system, driven by the stochastic forcing of wave and steady flows, can be assessed.

ACKNOWLEDGEMENTS

The authors thank Mark Pannell and Andrew Ashton for provding figures and for helpful discussions. The 'HUMOR' (Human Interaction with Large-Scale Coastal Morphological Evolution) Project, funded by the European Commission Framework Five (EVK3-CT-2000-00037), provided support for D. Huntley and T. O'Hare. G. Coco gratefully acknowledges support from the (New Zealand) Foundation for Research, Science and Technology, Contract C01X0218, Mitigating Weather, Flooding and Coastal Hazards.

LITERATURE CITED

AAGAARD, T. and BRYAN, K.R., 2003. Observations of infragravity wave frequency selection. Continental Shelf Res., 23(10), 1019-1034.

ALLEN, J.R.L., 1984. Sedimentary Structures: Their Characteristic and Physical Basis. Developments in Sedimentology 30 A/B, Elsevier, Amsterdam.

ASHTON, A., MURRAY, A.B. and ARNAULT, O., 2001.

Formation of coastline features by large-scale instabilities induced by high-angle waves. Nature, 414, 296-300.

ASHTON, A., MURRAY, A.B. and RUESSINK, G.B., (2003). Initial tests of a possible explanation for alongshore sandwaves on the Dutch coast. Proceedings of 3rd IAHR Symposium on River, Coastal and Estuarine Morphodynamics, RCEM 2003, Barcelona, Spain, September 1-5, 2003, A. Sanchez-Arcilla and A. Bateman (ed.), IAHR, Spain, pp. 320-330, ISBN 90-805649-6-6.

BALDOCK, T.E., O'HARE, T.J. and HUNTLEY, D.A., 2003. Long wave forcing on a barred beach. J. Fluid Mech.

CABALLERIA, M., COCO, G., FALQUÉS, A., And HUNTHEY, D.A., 2002. Self-organization mechanisms for the formation of nearshore crescentic sand bars, J. Fluid Mech., 465: 379-410.

COCO, G., O'HARE, T.J., And HUNTHEY, D.A., 1999, Beach cusps: a comparison of data and theories for their formation, J. Coastal Res., 15(3), 741-749.

COCO, G., HUNTLEY, D.A., And O'HARE, T.J., 2000, Investigation of a self-organisation model for beach cusp formation and development, J. Geophys. Res., 105(C9), 21991-22002.

COCO, G., HUNTLEY, D. A. And O'HARE, T. J., 2001. Regularity and randomness in the formation of beach cusps. Marine Geology, 178, 1-9.

COCO, G., BURNET, T.K., WERNER, B.T., and ELGAR, S., 2003a, Test of self-organization in beach cusp formation, J. Geophys. Res., 108(C3), 3101, 46.1-46.11.

COCO, G., BURNET, T.K., WERNER, B.T., and ELGAR, S., 2003b, The role of tides in beach cusp development, (under review).

FALQUÉS, A., COCO, G., And HUNTLEY, D.A., 2000. A mechanism for the generation of wave-driven rhythmic patterns in the surf zone, J. Geophys. Res., 105(C10), 24071-24088.

GUZA, R. T. and THORNTON, E. B., 1985. Observations of surf beat. J.Geophy. Res., 90, 3161-3172.

HOLLAND, K.T., 1998, Beach cusp formation and spacings at Duck, USA, Continental Shelf Res., 18, 1081-1098.

HOLLAND, K.T. and HOLMAN, R.A., 1996. Field observations of beach cusps and swash motions, Mar. Geol., 134, 77-93.

HOLLAND, K.T. and HOLMAN, R.A., 1999. Wavenumber-frequency structure of infragravity swash motions. J. Geophys. Res., 104, 13479 13488.

HOLMAN, R.A. and BOWEN, A.J., 1982. Bars, bumps, and holes: models for the generation of complex beach topography, J. Geophys. Res., 87, 457-468.

HOLMAN, R.A., and SALLENGER, A.H., 1993. Sand bar generation: a discussion of the Duck experiment series, J. Coast. Res., Special Issue 15, 76-92.

HUNTLEY, D.A., GUZA, R.T., and THORNTON, E.B., 1981. Field observations of surf beat 1. Progressive edge waves, J. Geophys. Res., 86(C7), 6451-6466.

INMAN, D.L., and GUZA, R.T., 1982, The origin of swash cusps on beaches, Mar. Geol., 49, 133-148.

LANDRY, W., and WERNER, B.T., 1994. Computer simulations of self-organized wind ripple patterns, Physica D, 77, 238-260.

NISHIMORI, H., and OUCHI, N., 1993. Formation of ripple patterns and dunes by wind-blown sand, Phys. Rev. Lett., 71(1), 197-200.

OUCHI, N., and NISHIMORI, H., 1995. Modelling of wind blown sand using cellular automata, Physical Review B, 52(6), 5877-5880.

PANNELL, M. A., O'HARE, T. J. and HUNTLEY, D. A., 2003. Modelling sand ripple development by self-organisation in unsteady flows. Proceedings of the 28th International Conference on Coastal Engineering (Cardiff, Wales). J McKee Smith (ed.). World Scientific, New Jersey. Pp. 2837-2849.