11th Australasian Conference on Coastal and Ocean Engineering

Coastal Engineering - A Partnership with Nature

Sheraton Breakwater Hotel, Townsville
Queensland, Australia

23-27 August, 1993

Behaviour-Oriented Models Applied to Shoreface Profile Evolution

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SUMMARY A possible approach for the development of simple predictive methods of shoreface profile evolution is described. By application of a detailed process-based, cross-shore morphodynamic model and of some inductive assumptions we build simple descriptions which reproduce possible behaviours of the upper zones of shoreface profile as a function of time. The paper introduces the model concept and describes its application on the base of diffusion-type formulations while distinguishing time scales from seasons, to years and decades. These scales correspond to bar and berm formation, to the life-time of profile nourishments, as far as major human induced modifications are concerned, and to the time scales of weather pattern modifications and sea-level rise as far as natural effects are concerned.

INTRODUCTION

We consider uniform sandy beaches of several km's length where we assume that the along shore variation of the average coastal profile and of basic hydrodynamic processes can be neglected. On the contrary, the processes on the cross-shore direction are important in determining the profile evolution.

In this situation, *large scale coastal behaviour* can be computed on the base of the principle of sand-mass conservation and of geometric rules (such as the well known Bruun rule) that allow the evaluation of the horizontal and vertical translation of sandy beaches and the change in position of the coastline. This *static* approach does not require a rigorous definition of the involved processes but rather their parametric representation. Nevertheless it allows to evaluate possible scenarios of beach morphology evolution over a variety of time scales.

For coastal management applications however the *dynamic* evolution is also of interest. For instance it is important to define the speed of response of profile nourishments or sand extractions. The problem is that in the scales larger that the ones where processes are well known and experimental data are available it is difficult to set up efficient and reliable process-based models.

Our approach tries to overcome these difficulties by reproducing the qualitative behaviour of the profile evolution while maintaining a parametric representation, thus using behaviour oriented models. The qualitative behaviour to be reproduced may be based on field evidence and on specific aspects of behaviour inferred from the use of process models. The general objective is to obtain modelling tools that may be applied in a context where little experimental information (especially historical one) is available, with the aid of validated short term process-based models. They should be able to reproduce static conditions but also to give an assessment of the dynamic transitions between different static conditions. These models may result of great use for quick preliminary evaluations and for possible insertion into general concepts which do not rely on details but rather on efficiency.

THE SCALES OF INTEREST

The cross-shore transport, thus the variations in the coastal profile, is mainly responsible for the short term fluctuations in the coastal morphology. The long term evolution is the result of residual effects of the short term fluctuations both from gradients in the long-shore and cross-shore directions. Here we assume gradients in the long-shore direction not to be present or negligible.

We distinguish the scales of profile behaviour as indicated in Table 1. Our main interest is in the two larger scale processes. The shorter scale is today well treated by what we would define *short-term process-based models* (describing hydrodynamics and sediment transport on small space and time scales) which are now being extended on the so called medium-term. Time and length scales of our topic are longer than years and larger than the surfzone which implies that we are dealing with what we would define as *long-term modelling*: modelling on a time scale longer than can be handled by existing validated process-based (mathematical-physical) models. See De Vriend et al. (1) for a review on long-term modelling.

The profile development on the scale of years to a decade is most probably not well represented by process based models, both because of possible deficiencies and because in reality there will be more than just cross-shore processes responsible for the profile development.

Physical Process	Cross-shore Length Scale	Approximate Time Scale
Response to Sea-Level Rise	Total Shoreface to Inner Shelf	Decades to a Century
Influence of Human Activities	Upper to Middle Shoreface	Years to a Decade
Surfzone Bar Formation and Change	Surfzone	Storms to a Year
Hydrodynamics and Sediment Transport	Surfzone	Storm

Table 1 - Time and length scales of profile evolution

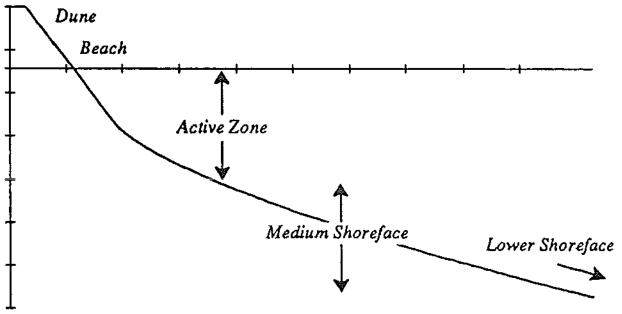

Figure 1 - Shoreface Profile components

BEHAVIOUR ORIENTED MODELLING

Possible formal approaches to extend the use of process based models may be based on the manipulation of the available mathematical formulations to simplify the hydrodynamic input conditions (input filtering), or to simplify the physical processes (process filtering). The first approach is based on the idea that we can describe long-term residual effects with short-term process based models driven by representative inputs. The second approach is based on the idea that, by using either formal integration or simplification methods, the models can be reformulated at the scales of interest.

These approaches appear to be useful in a number of practical situations however, even if formally correct, they present a number of practical difficulties that do not allow to solve the problem completely on the larger scales when either computational resources or available data are lacking. This implies that we have to fall back on inductive concepts like in Stive et al. (2). In practice this means that we have to adopt some assumptions based on our physical intuition and our expectations of the process behaviour. This approach may be termed *behaviour oriented modelling*. In order to analyse our results and to obtain predictive methods, we also rely on system dynamics related approaches to "describe" the behaviour.

The behaviour oriented modelling approach tries to overcome the practical difficulties by directly reproducing the qualitative behaviour of the profile evolution while maintaining a parametric representation. In practice this approach tries to "implicitly filter" both inputs and processes. The qualitative behaviour to be reproduced may be based on field evidence and on specific aspects of behaviour inferred from the use of process models.

The practical idea behind the approach is to map the behaviour of the coastal system, as observed in the field or from process-based model runs with real life input conditions onto a simple mathematical model that exhibits the same behaviour under well defined operating conditions. In this sense the model does not need to have any explicit relationship with the underlying physical processes.

With reference to Figure 1, in Table 2 we list behaviour and displacement of the various profile zones which may be of interested on the scales described in Table 1.

Profile Zone	Behaviour and Displacement
Active Zone	• Invariant Yearly Averaged Profile Shape • Upward Displacement due to Sea Level Rise • Shoreward Displacement due to: *upward displacement with sea level rise* *aeolian transport into the dune area* *sediment losses via longshore transport* *downwelling transport on the shoreface* • Seaward Displacement due to: *wave-induced onshore transport* *sediment supply via longshore transports* *upwelling transport on the shoreface*
Middle Shoreface	• Inclining or Declining depending on: *displacement of the active zone* *declining or inclining lower shoreface*
Lower Shoreface	• Declining and Eroding in Case of: *predominance of upwelling transports* *sediment losses via longshore transport* • Inclining and Accreting in Case of: *predominance of downwelling transports* *sediment supply via longshore transports*

Table 2 - Large Scale Behaviour and Displacement of Profile Zones (De Vriend et al. (1))

IDENTIFICATION OF THE BEHAVIOUR

In order to identify interesting behaviour, in the smaller scales we have evidences and data from the real life to rely on. On the contrary, in the longer scales, as far as real life data are missing, we may rely on simulations with the short-term process based model like in Stive et. al (3). Our choice was Roelvink and Stive (4) model which has been run on all the scales of interest up to many years with synthesized and observed wave climate as hydraulic input.

When necessary an "ideal" profile has been applied as the initial profile for the calculations. We term the Dean-Moore-Wiegel profile (DMW-profile) which consists of the equilibrium profile with a grain diameter dependence in the proportionality constant as described in Dean (5). Near the waterline, however, we adopt a constant slope m, related to the grain diameter and the exposure of the coast following Wiegel (6), as follows:

$$x_e(z) = \begin{cases} \dfrac{z}{m} & z < z_T \\ x_0 + (\dfrac{z}{A})^{\frac{3}{2}} & z > z_T \end{cases} \qquad (1)$$

where z_T is the depth at which the linear slope is tangent to the concave profile.

For what concerns the input conditions we basically refer to wave inputs and water level variations. In particular, following Hallermeier (7), we use to adopt the nearshore wave climate synthesis of Thompson and Harris (8) that provide a year distribution for nearshore wave heights as a function of the yearly mean Hs. Stive et al. (3) assumed that this distribution may be "extrapolated" to reach a multiple years climate.

Figure 2-4 briefly show from a qualitative point of view some of the interesting behaviours that might be reproduced, while Table 3 briefly summarizes the results.

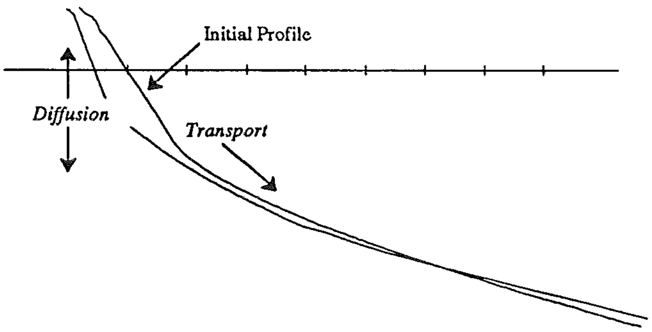

Figure 2 - Possible profile change on time scale of decades

Stive et al. (3) adopted the following approach to generate results on the spreading behaviour of nourishments. By using a synthesized or schematized wave climate as an input, pairs of profile evolutions are generated by the Roelvink and Stive model: one for an undisturbed, ideal profile (giving the "autonomous" development) and one for a disturbed, ideal profile, which is identical to the former except for the nourishment. Our basic assumption is that the spreading can be derived by comparing a nourished profile development with an autonomous profile development.

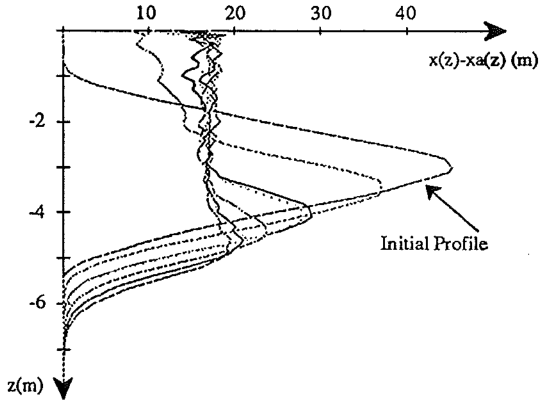

Figure 3 - Spreading of nourishment on time scale of years

The spreading of the nourishments closely resembles the smoothing out of a "disturbance" on an otherwise equilibrium profile. This smoothing process shows a shoreward asymmetry: the smoothing is stronger at the shoreward side. Associated with this asymmetry, the part of these artificial disturbances tending to move onshore exceeds the part tending to move offshore (Figure 3). And finally, the time scale of adjustment after a disturbance increases rapidly with depth. Similarly we have evidences of the fact that holes along the profiles (i.e. borrow areas) are filled as if the sediment around it would diffuse.

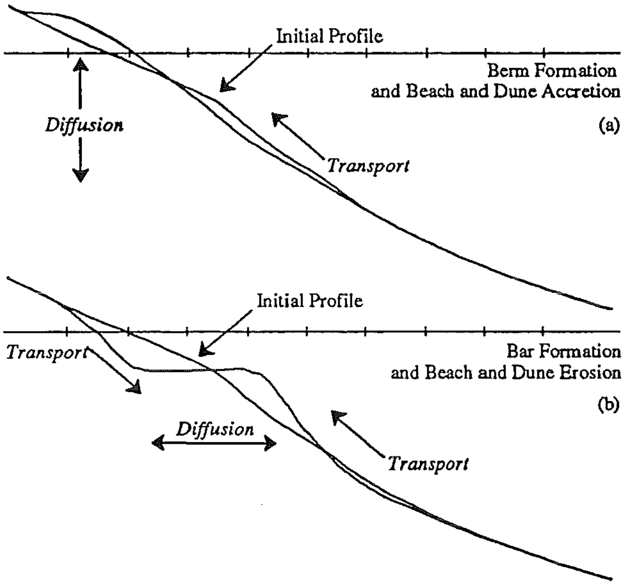

Figure 4 - Possible profile changes on seasonal time scale

Observed Process	Qualitative Behaviour
• Profile Displacement in the Long Term (Fig. 2)	Inclining Profile Looks like a "diffusion" of sediment in the upper part of the profile
• Spreading of Sediment Supplies (Fig. 3)	The Spreading Looks like a "diffusion"
• Accreting Profile • Berm Formation (Fig. 4a)	Inclining Profile Looks like a "diffusion" of sediment in the upper part of the profile
• Eroding Profile • Bar Formation (Fig. 4b)	Declining Profile Looks like a "diffusion" of sediment around the bar

Table 3 - Qualitative Behaviour to be reproduced

Diffusion is considered as the tendency to "smooth gradients"; thus declining may be seen as a local diffusion as a function of the cross-shore position, inclining as a local diffusion as a function of depth. In favor of the hypothesis of diffusion there is also the way the profile responds in time (fast initial response and slow settlement).

DIFFUSION-TYPE FORMULATIONS

These observations allow us to apply *diffusion-type formulations* for models, thus identifying the fundamental parameters as the space-varying coefficients of a rather simple dynamic equation. The variation of the coefficients, in particular the diffusion coefficient, permits the representation of the variation of the morphological time scales along the profile. It is important to note that the choice of the class of diffusion-type model equations is not derived rigorously from any basic process-based model equations, it is selected only because its solution exhibits the proper behaviour for our application.

With appropriate initial and boundary conditions the *cross-shore position* can be described as a function of *profile depth x(z)*. The following formulation is an extension of the n-line model with an infinite (but finite in the numerical discretisation) number of contour lines.

$$\frac{\partial x}{\partial t} = \frac{\partial}{\partial z}\left(D(z)\frac{\partial x}{\partial z}\right) + S(t,x,z) \qquad (2)$$

S(t,x,z) is an external source function which depends on time, on the cross-shore distance (x) and on the profile depth (z). While D(z) is a depth dependent diffusion coefficient. The vertical variation of the diffusion coefficient allows us to represent the variation of morphological timescale with the vertical position, and an asymmetry in the long-term residual sand displacement across the profile. The idea is to have all the information about the typical site climate, the sand characteristics and the degree of activity of the various profile zones summarised into D(z).

The calibration of this parameter is the key element of the model definition: all information, on hydraulic and sediment characteristics as well as on shorter-term dynamics is stored in it. All the human induced inputs as well as other "natural corrective" terms are summarised into S(t,x,z).

In our first tests we used to rely on profile data generated by the process-based model. The diffusion coefficient is "adjusted" by an identification routine in order to reach an optimal agreement between reference profile data and profile data generated by eq. (2). The comparison is not necessarily made point by point but can be done on "aspects" of profile evolution. Our approach is based on the preliminary definition of the "shape" of the coefficient and the subsequent quantitative calibration.

The final objective of the experience that can be gained in this way is to be able to directly express the parameters that give shape and value of D(z) as functions of mean environmental parameters (wave input and water level variations) and of geometrical characteristics.

We may assume the diffusion to be at maximum at the top and almost negligible at the bottom. This is well in agreement with physical considerations. If we refer to an hypothetical equilibrium situation, characterized by $\frac{\partial}{\partial z}\left(D(z)\frac{\partial x_e(z)}{\partial z}\right) = \frac{\partial x_e(z)}{\partial t} = 0$, it is possible to show that a diffusion coefficient that gives the DMW profile as an equilibrium solution is:

$$D(z) = C_D \begin{cases} m & z < z_T \\ \dfrac{2}{3}\dfrac{A^{\frac{3}{2}}}{z^{\frac{1}{2}}} & z > z_T \end{cases} \qquad (3)$$

Where C_D is a multiplicative constant which actually gives the *speed of response* of profile to reach the equilibrium. It could be demonstrated that the time dependence of the response is of exponential type (in agreement with Kriebel and Dean (9) or Kriebel and Dean (10)).

Of course it has to be noted that this is based on the assumption that the seaward boundary is infinitely far from the beach boundary. It is however an useful reference to be taken into account in order to define possible shapes of D(z); see for instance Figure 5.

The same basic equation may be applied to describe the evolution of the *profile depth z(x)* as a function of the *cross-shore position*:

$$\frac{\partial z}{\partial t} = \frac{\partial}{\partial x}\left(D(x)\frac{\partial z}{\partial x}\right) + S(t,x,z) \qquad (4)$$

There is even more empiricism in this formulation as far as D(x) has to be shaped in relation to "where we want" the sediment to diffuse. In this case it is useful to associate the peak of the diffusion coefficient with the position where the waves break (Figure 5). Any empirical relation for the definition of this position may be considered. We may for instance rely on Gouda or Sunamura criteria relating breaking parameters (breaker height H_B, and breaker depth h_B) to deepwater conditions as described in Horikawa (11).

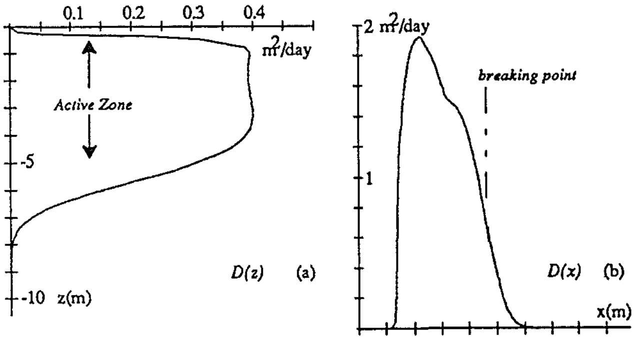

Figure 5 - Diffusion coefficient shapes

Possible Extensions to eq. (2) and (4) are the following:

$$\frac{\partial x}{\partial t} = \frac{\partial}{\partial z}\left(D(z)\frac{\partial x}{\partial z}\right) + \frac{\partial}{\partial z}(V(z)x) + S(t,x,z) \qquad (5)$$

$$\frac{\partial z}{\partial t} = \frac{\partial}{\partial x}\left(D(x)\frac{\partial z}{\partial x}\right) + \frac{\partial}{\partial x}(V(x)z) + S(t,x,z) \qquad (6)$$

With the direct inclusion of transport term it is of course possible to better reproduce some peculiar aspects of modification of profile shape. Both formulations have in principle the potential to reproduce the different situations at the extent they are simple enough.

A clear practical limitation is represented by the stationarity of the transport and the diffusion term in the formulation. What we may expect is a sort of "mean evolution" in the modelled period. These aspects are governed by the way we conduce the comparison of profiles. The stationarity has also strong implication on the behaviour of the solution and, on ultimate analysis, on the character of the profile evolution that has to be reproduced. This means that all the listed model equation are restricted to reproduce profiles which are evolving in a constant way (e.g. constantly eroding or accreting). Irregurarly evolving profiles result from irregular transport mechanism and would at least require time varying transport and diffusion term. In practice in such situation is extremely difficult to make the identification procedure converge to a solution.

Another important aspect that must be taken into account is that the rate of activity, as qualitatively indicated by Hallermeier (7), will depend not only on the direct hydraulic impact, i.e. not only on wave input, currents and so on, but also on the time scale considered.

Another potential problem that has to be taken into account with such formulations is the fact that sand-mass conservation is not a priori guaranteed

The same basic equation may be applied to describe the evolution of the actual cross-shore position x(z)-xe(z) referred to an "equilibrium profile position", or the actual cross-shore position x(z)-xa(z) referred to an "autonomous profile position" that well represent the situation that arise when introducing a disturbance along the profile. In fact the latter is the formulation currently being applied by De Vriend et al. (12) for the cross-shore spreading of nourishment. Summarizing the list of possibilities is the following with the possible applications listed in Table 4:

- Profile Depth as a function of Cross-Shore Position;
- Cross-Shore Position as a function of Profile Depth;
- Cross-Shore position referred to "Equilibrium Profile";
- Cross-Shore position referred to "Autonomous Profile Evolution".

Formulation	Applicability
x(z)	Response to Sea-Level Rise
x(z)-xa(z)	Nourishment or Sand Extraction (with the support of a Process Based Model)
x(z)-xe(z)	Nourishment or Sand Extraction (Displacement from equilibrium)
z(x)	Eroding Profile on the Short scale
x(z)	Accreting Profile on the Short Scale

Table 4 - Applicability of the various formulations

Some words should be spent on how to select a proper formulation in the case of the shortest scale. The form of the coastal profile and the variations in this form are mainly governed by cross-shore transports. These cross-shore transports and thus the coastal profiles, are closely related to wave motion and to sediment characteristics. In this respect an important distinction is between bar profiles and step profiles, where the first may be identified as eroded profiles and the second with accreted profiles. From trial calculations it was concluded that the principal process variable is the wave steepness.

In principle it is easy to see that z(x) applies more for the description of the erosion process rather than accretion process. Analogously x(z) applies more in case of berm formation rather than bar formation. These observations suggest the possibility to switch from one formulation to another on the base of a criterion to discriminate between accretion and erosion conditions or on the base of a simple condition for bar formation. Typical parameters to consider are wave steepness, sediment grain size, bottom slope and so on, as described in Horikawa (11), giving the possibility to formulate the criterion in relation with site specific characters and (offshore) input condition on the proper time scale.

Of course in order to use such criterion we move to the problem of selection of representative wave condition thus establishing a link with the subject of input filtering (see De Vriend et al. (1)).

BOUNDARY CONDITIONS

We have to define a beach boundary condition and a seaward boundary condition. Boundary conditions must be defined in relation to the specific formulation chosen and to the specific application. In principle we want to have a "no change" boundary condition at the seaward boundary. This should basically correspond in fixing the position but also in the specification of no flux. The simultaneous application of these two conditions is not possible directly but it is possible to play with the coefficients. In order to specify the boundary condition we have to rely on a representation at least at conceptual level of what is over the boundaries or what are the boundaries. The two boundaries present different difficulties and specific characters.

Onshore we should specify at least a simplified dune erosion scheme to be coupled with the dynamic model in order to reproduce the role of dune as reservoir or supplier of sand.

Seaward the fundamental problem is to define where the boundary should be. For the processes we are considering this boundary is placed on the lower shoreface. A valuable and useful approach to determine the seaward extent (closure depth) was developed by Hallermeier (7), who defined it as the annual shoreward boundary of his shoal zone. In general a time scale dependence of the seaward extent of the active zone (the closure depth) can be expected. Insight into the time scale dependence of the closure depth and the relative activity across the active zone is of importance for qualitatively more accurate prediction of behaviour.

On the other hands, from the other side, it is also true that we may use hypotheses on the characters of the behaviour and "fitted coefficients" to gain insights into the time scale dependence of the closure depth or the position of the seaward boundary.

Formulation	Beach Boundary	Sea Boundary
x(z)	$x' = x'_R(0)$	$x_S = x_S(0)$
x(z)-xa(z)	$x_R' = 0$	$x_S = x_S(0)$
x(z)-xe(z)	$x_R' = 0$	$x_S = x_S(0)$
z(x)	$z_R = z_R(0)$	$z_S' = 0$
x(z)	$x_R = x_R(0)$	$x_S = x_S(0)$

Table 5 - Definition of possible boundaries

A list of possible boundary conditions is presented in Table 5. They should be considered only as indicative (especially the last two) as far as they are also related to the values of the (diffusion and advection) coefficients at the boundaries and to the possible formulations of the transport of sand at beach boundary.

CONCLUSIONS

By application of a detailed process-based, cross-shore morphodynamic model and some inductive assumptions, the characters of shoreface profile evolution are being studied in relation to time scales. The results give qualitative and quantitative indications on how to reproduce such characters in simple way.

The application of behaviour-oriented modelling approach we are working on is quantitatively based on diffusion-type equations. The coefficients of such equations are at the moment derived by using a parameter identification method with "experimental" data produced under well defined boundary and initial conditions by using traditional process-based model.

We plan further work to generalize our results in order to be able to handle a variation of boundary and initial conditions, both for the purpose of practical applications and scientific understanding. We also intend to compare and verify our findings with real life data.

Periods from storm to seasons are interesting as far as they allow us to check the concept against well validated short term process models. However the real longer term objective of our activities is to arrive at a predictive method to establish the behaviour of shoreface profile on the longer scales. One objective of our study is to assess whether and to what extent the diffusion model concept stands in practice, and to find simple and manageable parameterized expressions for the diffusion coefficient as a function of boundary conditions, geometrical features and environmental parameters (in particular wave climate data and water level variations).

What is obviously needed more and more is experience about application. The concept needs to be applied in order to gain substance. The support given by process based models is welcome and necessary but real life data would be even more welcome.

As soon as new experimental information will become available the behaviour oriented concept will play its role in summarizing it for situations where few data are available and quick evaluations are required.

ACKNOWLEDGMENTS

This work has been carried out as part of the European Community MaST G6 Coastal Morphodynamics Project (Directorate General for Science, Research and Development, MaST Contract no. 0035-C) and with the support of the Coastal Genesis Research Programme of The Netherlands (Rijkswaterstaat, Tidal Waters Division) and of the Researchers of Excellence Programme for Catalan Universities of the Generalitat de Catalunya.

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