Memo

To
RWS-WVL
Quirijn Lodder

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From	**Direct line**	**E-mail**
Dirk-Jan Walstra	+31(0)88335 8782	dirkjan.walstra@deltares.nl

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CONTENTS

1 Introduction

Based on a concise set of recent publications the present state of the art is given regarding the predictive capabilities of process-based morphological models for nearshore nourishments.

First a general overview is given of the reported Delft3D and Unibest-TC applications on nearshore bar dynamics and/or nourishments and recent insights on nearshore bar dynamics are summarized. Based on these outcomes an assessment is made to what extent the present process based (PB) models are capable to simulate the nearshore morphodynamics and their validity to be used to design and evaluate shoreface nourishments. Finally, a general modelling approach is presented as well as an overview of the possible improvements in the models.

The memo was written by dr.ir. Dirk-Jan Walstra and reviewed by dr.ir. Bart Grasmeijer.

2 Overview of nearshore model applications and relevant processes

Grunnet (Grunnet et al., 2004; Grunnet et al., 2005 and Grunnet and Ruessink, 2005) studied the shoreface nourishment carried out as part of the NOURTEC experiment (Hoekstra et al., 1994) on the central part of Terschelling. This nourishment was constructed in 1993 and located in the trough of a bar-trough system. Besides an extensive phenomenological analysis, Grunnet also performed a detailed modelling study in which Delft3D was applied in 3D. Despite the advanced 3D approach and the calibrated parameter settings which minimised the RMS-error (averaged over the area of interest), the bars did not survive in the morphodynamic simulation, instead the bars flattened. Additionally, the vertical and horizontal growth of the middle bar as a result of the observed onshore movement of the nourishment was not reproduced. Overall, modelling performance of cross-shore bed-level changes was extremely poor and the observed cross-shore migration and development of bars was not well reproduced; bars appeared to diffuse rather than migrate. On a large scale of overall profile behaviour derived through bulk volumes integrated over large spatio-temporal scales (several kilometres and months, respectively), the predictive capabilities were better and the model gave a reasonable representation of the profile development. The overall effect of the nourishment related to lee and feeder effects were reproduced: integrated over distances on the order of the alongshore length of the nourishment, the sedimentation at the shoreline and the onshore movement of nourished sediment were well predicted. The poor performance on the cross-shore bar response was mainly attributed to the absence of the roller model (Nairn et al., 1990) and breaker delay effects (Roelvink et al., 1995) in the applied model version of Delft3D. Two decades later Walstra (Walstra et al., 2012) showed that these processes allowed for an accurate reproduction of inter-annual cross-shore bar dynamics (see description further below).

Van Duin et al. (2004) studied one of the first regular shoreface nourishments carried out at Egmond in 1999. For this purpose, both Delft3D and the profile model Unibest-TC were applied. The findings for Delft3D were comparable to Grunnet. On aggregated scales the model was able to provide reasonably accurate predictions and it provided insights in the effects of the shoreface nourishment on the sediment transport. The poorer performance on smaller scales is likely due to the absence of the roller model and breaker delay in this study, although this was not mentioned in the article. The application of Unibest-TC showed that this model has predictive skill for the central parts of the nourishment. This is mainly due to the fact that this model has both processes included. The decreasing performance towards the distal ends of the nourishment is attributed to the presence of alongshore gradients in the hydrodynamics and sediment transports originating from the alongshore non-uniform bathymetry.

Walstra et al. (2008) studied the subsequent nourishment at Egmond in great detail. In addition to the application of Delft3D in area mode, the model was also applied in profile mode. Although the considered time scales were considerable shorter, the application in area mode showed a comparable performance as for the Grunnet and Van Duin studies. Interestingly, the application of Delft3D in profile mode showed predictive skill that was qualitatively similar to the Unibest-TC application in van Duin et al. (2004). No in-depth analysis was performed that could explain the differences between the area and profile mode applications of Delft3D.

It was found that the assimilation of shoreface nourishments in the coastal system involves a strong interaction with the pre-existing bar system (Ojeda et al., 2008; Bruins, 2016; de Sonneville and van der Spek, 2012; Van der Spek and Elias, 2013). The typical placement of a shoreface nourishment just seaward of the outer bar temporally reverses the cycle and induces a landward migration of the bars. As the shoreface nourishment is absorbed in the coastal system, it becomes the new outer bar (e.g. Van Duin et al., 2004). At the distal ends of a shoreface nourishment often bar switches are present due to the distinct phase difference in the bar migration cycle it induces. Given the importance of the bar-nourishment interaction, the efficacy of shoreface nourishments is expected to benefit from an improved understanding of the nearshore bar dynamics. The following features that together encompass the main characteristics of the inter-annual bar morphology were therefore investigated by Walstra (2016):

- The cross-shore transient bar amplitude response, that is, the transition from bar growth in the intertidal and across surf zone to bar decay at the seaward edge of the surf zone.
- The intra-site alongshore variability in cross-shore bar position, bar amplitude and the occurrence of non-persistent bar switches.
- The inter-site variability in the bar cycle return period which is typically accompanied by a persistent bar switch that separates two sections with different bar cycle return periods.

Walstra (2016) adopted a comprehensive study approach in which observations of the nearshore morphology were combined with detailed Unibest-TC simulations in which the measured wave and water level conditions were used to force the model. A reference model was constructed, calibrated and validated. The reference model was applied to a single bar cycle return period at Noordwijk (The Netherlands) to calibrate the model's free parameters. The Noordwijk model acted as a reference for additional simulations at Egmond (The Netherland) and at Hasaki (Japan) to address the specific characteristics of the nearshore sandbar morphodynamics as outlined above.

The cross-shore transient bar amplitude response was found to be strongly related to incident wave angle, which in turn pointed to the relevance of the longshore current induced sediment transports. More specifically, the cross-shore distribution of the sediment stirring is affected by the longshore currents in such a way that the cross-shore sediment transports distribution shows a spatial shift relatively to the bar crest position. In cross-shore regions where wave breaking is prevalent this shift causes bar growth, whereas in regions further offshore this spatial shift is absent as the sediment transport is dominated by cross-shore processes and consequently bar decay prevails (Walstra et al., 2012).

Bar switching is typically an indication of a distinct phase shift in the bar cycle (Wijnberg and Terwindt, 1995; Shand, 2003) where an outer bar is attached to an inner bar or where bars are detached completely, resulting in a fork-like configuration. Although bars can switch under natural conditions, shoreface nourishments may also trigger switches. For example at Egmond, The Netherlands, the net offshore bar migration was delayed immediately landward of a shoreface nourishment, while elsewhere net offshore bar migration continued. This spatially discontinuous offshore migration resulted in bar switches that lasted about one year (Ojeda et al., 2008).

The intra-site alongshore variability in bar amplitude and cross-shore position was investigated in Walstra et al. (2015), more specifically: 1) to what extent cross-shore processes can initiate, amplify or dampen alongshore sandbar variability on km-scale and 2) to identify the relative importance of wave forcing and antecedent morphology on the predicted large scale alongshore variability. It was found that the alongshore averaged bar morphology at each side of a bar switch responded differently to (energetic) wave forcing, whereas such a response was absent for the less energetic wave forcing. The water depth above the bar crest was found to be of primary importance as, for a given wave forcing, it largely controlled the bar amplitude and bar migration response. Sensitivity analyses systematically varying wave forcings, showed that a specific state of the morphology subjected to a period with energetic wave forcing can result in an alongshore varying response (i.e. increase in the alongshore variability of the bar amplitude and cross-shore position), whereas for a different bar morphology such a response was absent for similar forcing. Walstra et al. (2015) concluded that the generation of bar switches, similar to the findings of Shand et al. (2001), is the outcome of a particular morphological state and wave forcing combination.

The inter-site variability in bar cycle return period is primarily governed by the profile bed slope in the surf zone. The importance of the bed slope implies that water depth above the bar crest and the morphodynamic feedback loop primarily govern the bar cycle return period. Despite more intense wave breaking and an initial enhanced offshore migration rate, the overall effect of a steeper profile is an increased return period as it causes:

1. A relatively larger increase in water depth above the bar crest as a bar gradually migrates offshore which in turn causes fewer waves to break on the bar and consequently reduces the offshore bar migration.
2. Enhanced wave breaking results in relatively larger bars that will also reduce the offshore migration.
3. An increased water depth where bar decay sets in due to more intense wave breaking. Combined with the more energetic wave climate this increases the bar zone width at Egmond by about 200 m compared to Noordwijk for example. Therefore it takes longer for the bars to migrate across this region (the observed offshore migration rates would lead to a five year increase in the return period).

Recently Dubarbier et al. (2017) successfully applied a depth-averaged morphodynamic model to simulate a full downstate beach sequence (Wright and Short, 1984). This is the first publication in which a process based area model is able to predict the transition from (1) the longshore bar and trough (LBT) state, sometimes referred to as storm profile, characterized by a continuous alongshore uniform offshore bar to (2) the rhythmic bar and beach (RBB) state characterized by a detached crescentic sandbar to (3) the transverse bar and rip (TBR) state with shore-attached shoals separated by deep rip channels to (4) the low tide terrace (LTT) characterized by a shore-attached alongshore ridge cut by shallow rip channels. From their numerical experiments Dubarbier et al. (2017) found that the contribution of cross-shore sediment transport, namely, the imbalance between the sediment transport driven by the undertow, wave skewness, and gravitational downslope effects, was a major impediment to simulate beach state sequences. Especially, the onshore sediment transport driven by wave skewness (which controls the onshore sandbar migration) and the gravitational downslope (which primarily balances the wave skewness driven sediment transport) are two processes that had not been identified as crucial for the simulation of the transitions of bar states. This model application builds on the recent parametrizations of wave nonlinearities (Ruessink et al., 2012) and advances in cross-shore sediment transport using phase-averaged models (e.g. Walstra et al., 2012; Dubarbier et al., 2015; Fernández-Mora et al., 2015).

3 Potential application of PB models in nourishment designs and analysis

3.1 Relevant physical processes

Based on the above findings it is concluded that process-based models could contribute to the design and evaluation of shoreface nourishments. In terms of relevant processes Delft3D and Unibest-TC are the most appropriate models. For Delft3D the wave skewness formulations of

Ruessink et al. (2012) are currently implemented in Delft3D through collaboration with Utrecht University (Marcio Boechat; Phd student from prof. dr. Maarten Kleinhans). With this implementation the most dominant processes relevant for the shallow marine environment are included in Delft3D.

3.2 Considerations on nearshore PB-modelling

The current state of the art of PB-models always requires a site specific calibration on the observed morphology (e.g. Walstra et al., 2016). Calibration could be performed though the application of optimisation routines (e.g. the approach followed by Walstra et al., 2012) or a manual optimisation through parameter tuning based on expert judgement and sensitivity simulations. However, automatic calibration procedures are not practical at this stage for computationally intensive models such as Delft3D.

To evaluate the cross-shore interaction between a shoreface nourishment and the coastal system the Unibest-TC model is most appropriate. As the model assumes alongshore uniform conditions, its application is limited to the central part of nourishments. The model can be used in brute force mode and as such can be utilized to derive a limited set of representative wave conditions that could be used for area-modelling with Delft3D.

Delft3D in profile model has the potential to be used in a similar way as Unibest-TC, but this kind of application has not been carried out since Walstra et al. (2008). In area mode Delft3D can be used to evaluate the aggregated behaviour of shoreface nourishments.

The past decade a very limited number of modelling studies has been performed to evaluate shoreface nourishments. At the same time we have obtained better insight in the application of PB-models on inter-annual time scales (Walstra, 2016) and the ability of PB-based area models to simulate complex nearshore morhodynamic responses (Dubarbier et al., 2017). The time seems right for a renewed attempt to include PB-models in the nourishment design and analysis work flows. It is emphasized that the application should go beyond an evaluation of the model performance and should focus on the indicators that are relevant for the (Dutch) coastal management practice. An important limitation of the present models is their inability to simulate inter-tidal, beach and dune regions on longer than storm time scales.

In the next section a generic modelling approach is described with an exploratory focus on the profile and area modelling applications and the validation of the most recent model codes. Prior to embarking on a PB-model application, it is advised to develop a clear set of output indicators in close consultation with RWS-WVL counterparts. This should be the starting point and is hopefully complementary to the approach outlined below.

3.3 Tentative modelling approach

In this approach a comprehensive scope is presented in which profile and area models are used in concert.

The suggested modelling approach is described in a number of concrete steps. An application along the Holland coast (or central part of a barrier island) is assumed. Model specific aspects such as which parameters should be used for the calibration are not mentioned. The references in the previous sections are a good starting point for this purpose.

3.3.1 Model setup

1. Collection of relevant bathymetric and hydrodynamic data
2. Development of model grids. In the nearshore a cross-shore resolution of 2 – 5 m is required; in the longshore 10-20 m.
3. Steps specific for a Delft3D-Area model application

   a. types of boundaries: offshore water levels, lateral Neumann boundaries according to setup suggested in Roelvink and Walstra (2004).
   b. tidal schematisation is typically obtained using Latteux (1995), mostly using a single or double(semi-diurnal) representative (morphological) tide.
   c. wave schematisation (i.e. reduced set of wave conditions) can be obtained following the method outlined in Walstra et al. (2013). Additional considerations (e.g. consistent model settings and transport formulations can be found in Coastal Dynamics 2 lecture notes (Delft University of Technology) or the Deltares Webinar by Walstra (2011).
4. Steps specific for profile model applications (Unibest-TC and Delft3D)
   a. As the Unibest-TC model runs very fast, no input reduction is required. Measured wave conditions (Hrms, Tp, wave direction), water levels (vertical tide and surge) and horizontal tide can directly be imposed on the model using measured time series.
   b. The grid (cross-shore only) should have resolution of a 2 – 5 m in the nearshore zone.
   c. Typically a Jarkus profile can directly be used as input.
   d. Unibest-TC can be used to develop a reduced wave climate for Delft3D following the method described by Walstra et al. (2013)
   e. Application of Delft3D in profile mode with brute forcing is probably not feasible. However, the model can be applied with a large number of wave conditions compared to the area mode application. Furthermore, it can be used to calibrate the area model (see also next sub-section).

3.3.2 Calibration

1. Nourishments typically have a strong interaction with the pre-existing (barred) morphology and mostly have life expectancy in the range of 3 – 5 years. Therefore, calibration should cover similar time scales. Calibration will usually be focussed on the simulating the inter-annual bar morphology. However, if the study site has previously been nourished, a calibration on the observed development of such a nourishment is also an option.
2. The calibration should focus on the predicted morphology. Although the waves, hydrodynamics and sediment transports are also important, a good performance on these aspects does not guarantee reliable morphodynamic predictions.
3. The cross-shore development remains one of the most challenging aspects of nearshore process-based morphodynamic modelling. All models require a site specific calibration on this aspect. A good concept is to first calibrate the morphology in profile models and subsequently include the alongshore dimension.
4. Evaluation of the calibration should by based on pre-defined indicators such as skill scores (e.g. van Rijn et al., 2003; Ruessink et al., 2007; Sutherland et al., 2004), aggregated sediment budgets (sand volume changes in aggregated areas/box; e.g. Walstra et al., 2014), compositions of MKL-type volumes (e.g. changes of sand volume in horizontal “slices” of the profile and/or the temporal evolution bar volume, bar crest position, etc. (e.g. Bruins, 2016). Selection of the criteria should always be coupled to the purpose of the modelling. The MKL-approach is however less suitable for analysing and understanding profile developments. This is primarily originates from the fact that sediment transports is in the horizontal plane which can only be captured with vertical boundaries between areas (i.e. aggregated areas in plan view) and not by horizontal boundaries applied in the MKL-approach.
5. Besides a measure of quality, the calibration should also provide insight into the robustness of the predictions. This can be achieved by evaluating simulations with slightly different model settings, considering a different period or initial bathymetry. In

other words the performance should not be limited to a single skill score and/or indicator. A skills range should be provided.

3.3.3 Validation

1. Validation of the model(s) is typically performed on a different time period (but at the same location). It builds on the calibration and provides insight into the robustness of the model (see also previous point).
2. The same indicators as utilised in the calibration factor should be used.

3.3.4 Application

Here it is assumed that models can be used to select and optimise designs. Given the fact that model applications for shoreface nourishment designs has not been done for a decade. The first step will be to evaluate the abilities of models for this purpose as outlined in the paragraphs above. Only if these steps are successfully completed, an application to nourishment design optimisation is warranted.

1. Depending on the specific questions, models could assist in the analysis of an existing nourishment. For example, models could be used to play “what if” games with the intention to understand specific aspects of the observed development or to identify (and understand the role of) the dominant physical processes.
2. In case of design optimisation, models can be used to compare and evaluate different designs (based on indicators, see next point). Additional benefit could be obtained if insights into processes and working mechanisms are used to further optimise the selected design.
3. Although not critical, it is valuable to evaluate the nourishment with the indicators used in calibration and validation phases.

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