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Scale dependency of dune erosion models

Performance assessment of the DUROS and XBeach model for various experiment scales

Peter Brandenburg

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SCALE DEPENDENCY OF DUNE EROSION MODELS

Performance assessment of the DUROS and XBeach model for various experiment scales

Rotterdam, 25 November 2010.

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As fulfilment of the Master's degree
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Abstract

This report represents a study to the scalability of the dune erosion models. Dune erosion models are used for the safety assessment of the sandy dunes of the Dutch coast. Presently, the safety assessment is based on the relatively simple cross-shore dune erosion model DUROS. The empirical DUROS-model is designed for alongshore uniform coastlines. Since the DUROS-model is not qualified to assess storm impact in complex cases, a more generic model that includes the long-shore dimension can be a helpful instrument. In this study the DUROS-model is compared with the generic model XBeach. The XBeach-model contains a physical description of the most important processes that are of relevance to dune erosion in both cross-shore and long-shore direction. As the dunes are assessed to normative conditions that have never occurred, most models are based on laboratory experiments. Since DUROS and XBeach are based on the same lab experiments but predict different storm impact on real scale (DUROS estimates 40% more dune erosion), the lab-prototype conversion in the two models is different.

The above problem led to the next objective: getting a better understanding of the underlying causes for differences in storm impact predictions by DUROS and XBeach. From the objective, two research questions were formulated: *What causes the difference in storm impact predicted by DUROS and XBeach for reference conditions?* And *what consequences do these differences in storm impact have on the prediction for prototype scale?* In order to answer these questions, the laboratory results of a series of lab experiments (M1263) and a field case are studied. The research project M1263 contains 26 laboratory experiments on various scales over a range of 5-90. These experiments are chosen because the current DUROS-model was constructed with the results of these experiments. Secondly, a field case storm is investigated, the ’76 storm surge. The DUROS-model and the XBeach-model are applied to both cases.

When analyzing the M1263 experiments, the model distortion and the applied grain size were found to be very important for the intensity of dune erosion. The laboratory experiments were carried out by Vellinga and Van de Graaff in the late ’80. During the research program, a scaling rule was developed, in which the distortion rate (n_d/n_l) is a function of the lab scale (n_d) and the sediment fall velocity (n_{ws}). The scaling rule was created with the goal to converse erosion amounts between various scales. The DUROS-model was created with this relation and the experimental results.

The DUROS-model is very well capable of reproducing the large-scale experiments. However when applying the model to small-scale experiments, it was found that the model lacks performance, caused by incorrect simulation of the run-up zone. After implementing the run-up zone in the model (DUROS research version), the new model shows consistent (good) performance for all scales. The XBeach-model shows also good performance for large-scale experiments, but performs insufficient for small-scale. Since the model is process-based, it was chosen to adjust numerical parameters in order to be able to reproduce small-scale experiments. Six parameters were introduced that need to be changed for different scales: Three parameters of the avalanche model (dzmax, wetslp and hswitch), a cut-off water depth for the Stokes drift included return flow (hmin), a cut-off water depth for sediment transport (eps) and the near-bed turbulence (turb). The changes altogether lead to a model improvement of BSS≈0 to BSS≈0.5 for small-scale experiments. A better performance (BSS≥0.8) is obtained when the transport formulations in the model are adjusted.

In the field case of the ’76 storm three transects of the Dutch coast are chosen: Julianadorp, Bergen aan Zee and Castricum. The two models perform similar for the three cases in terms of predicted erosion amount. That the models predict differently for the reference case and for relatively ‘calm’ conditions, implies that the sensitivity of both models is different. A sensitivity analysis to the hydrodynamic and morphdynamic boundary conditions showed that the XBeach-model is less sensitive to the surge level, the sediment size and the steepness of the initial profile, compared to DUROS. DUROS is less sensitive to the wave period and for the wave height the sensitivities are fairly similar.

The two revised models showed a better performance for the experiments on various lab scales. For the prototype application the changes led to less difference between DUROS and XBeach.

Preface

This report represents the work that has been carried out during the master thesis project, with as subject, the scale dependency of dune erosion models DUROS and XBeach. This project finalizes the Master program at the Water Engineering and Management department at the University of Twente. The project was carried out at Deltares in Delft. The question for this research came from the research program for the development of a new tool for the safety assessment of coastal dunes (SBW-Duinen).

The thesis project started with lots of testing and getting familiar with the DUROS and XBeach model. During the project I struggled a lot with the Matlab program that is a very helpful tool if you know the codes. I spend several weeks on analyzing, rewriting and writing scripts for analyzing model performances and others.

I would like to thank my mentors Kathelijne, Jaap and Jan. Kathelijne for providing really hard questions every time we met, Jan for his supervision and Jaap for his patience and faith in me when I would rather throw my PC out of the window. Deltares provided me a nice environment to fulfil my research project with a lot of clever and pleasant colleagues. With a football competition, ice skating, wadlopen to Ameland and cycling, Deltares provided much more you could ask as a trainee. I had a lot of joy with my fellow graduation colleagues Trang, Martijn, Ingrid, Giorgio, Harm Gerrit, Sanne, Kees, Jorik and Rik who helped me and kept me from working at my project.

I would thank my friends from Enschede for keeping me from working during the weekend by trips to other European cities.

Last but not least, I would thank my parents, Albert and especially Susan for their support, faith and love that helped me finalizing my thesis that I proudly present to you.

Peter Brandenburg,

Rotterdam, November 2010

Contents

1 Introduction

1.1 Background

Since the early 19^{th} century, the Dutch Ministry of Transport and Water management (RWS) is engaged with managing water systems in the Netherlands. These water systems include rivers, lakes, estuaries, coasts, polders and islands. The initial goal was, 'water out and living in'. This policy led to a land without any real natural undisturbed system. Within this policy, land has several functions, and a lot of effort is undertaken to maintain these functions.

Over the past centuries, new polder land was created in the Netherlands from lakes and inundated areas. These areas, enclosed with dikes, are mainly situated below mean sea level and are as a result vulnerable for inundation during high water levels. In order to reduce this vulnerability, flood defence systems, like dunes and dikes, were reinforced and constructed. There is an ongoing debate in the Netherlands on the required safety level against flooding.

Given the desired safety level against flooding, normative hydrodynamic boundary conditions can be specified, which can be utilized to design a water defence. The hydrodynamic boundary conditions are revised every six years and are followed by a safety assessment of the primary water defence system. In case the primary coastal defence system consists of dunes, the assessment requires the application of dune erosion models.

Several models are available to assess storm impact on sandy dunes. In the Netherlands the detailed safety assessment of dunes (as prescribed in the Voorschrift Toetsen op Veiligheid (VTV) 2006) is presently based on the relatively simple cross-shore dune erosion model DUROS. The empirical DUROS-model has its origin in 1977 (Vellinga, 1986) and is designed for alongshore uniform coastlines. Since the DUROS-model is not qualified to assess storm impact in complex cases (like strongly curved coastlines, coastlines near inlets and coastlines with concrete structures), a more generic model that includes the long-shore dimension can be a helpful instrument in an advanced assessment. This type of model contains a physical description of the most important processes that are of relevance to dune erosion in both cross-shore and long-shore direction.

1.2 Problem

In situations where the safety assessment with the DUROS-model is not adequate, administrators can decide for a more advanced assessment with generic models. Van Thiel de Vries (2009) compared the DUROS-model with the process-based models, DUROSTA (Steetzel, 1993), CROSMOR (Van Rijn, 2008) and XBeach (Roelvink et al., 2009). It was found that for a simple alongshore uniform coast, the erosion volumes of generic models did not correspond well to the erosion volume obtained with the DUROS-model, as process-based models predicted on average about 40% less erosion. It was hypothesised that the differences could be attributed to the wrong up-scaling of the flume (laboratory) profiles to prototype (real or field scale) conditions (DUROS) or by scale effects in the implemented physics in generic models. In the latter case, the calibration parameters derived from (scaled) lab experiments may not be valid for the prototype application and some physical processes might be missing in the model.

This hypothesis is in line with results from a study within the SBW-research project in which different dune erosion models (DUROS+ (Van Gent et al., 2008), DUROSTA (Steetzel, 1993), SBeach (Wise et al., 1996) and XBeach (Roelvink et al. 2009)) were compared (SBW-Duinen2, 2008). The comparison of the models showed they perform differently with depth scale. The study revealed that XBeach has the largest potency for application on various scales.

Problem definition
Currently, the empirical DUROS-model is used for the safety assessment of coastal dunes. This model was constructed with the results of laboratory tests and is only applicable to those parts of the coast that are approximately uniform alongshore. To enable the application of the generic XBeach-model to predict dune erosion in more complex cases, the output from XBeach and DUROS should resemble for simple cases.

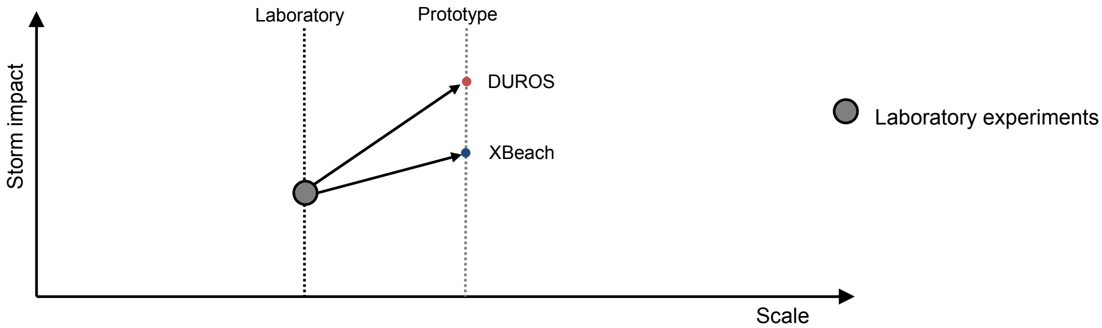


Figure 1.1: Storm impact on various scales: DUROS and XBeach predict similar storm impact on laboratory scale (gray circle) but deviate for prototype application (coloured circles).

The current problem can be formulated as, empirical and process-based model concepts perform differently for cases on different scales. Both models were created (in case of process-based: calibrated) with the results of several laboratory experiments. The fact that the models perform differently for the (prototype) reference case should imply that the lab-prototype conversion in both models is different (black arrows in figure 1.1). In this study, DUROS and XBeach are being analyzed in order to obtain more insight in the difference in their model approach and therefore how they simulate storm impact.

1.3 Objective

The objective of this study is to get a better understanding of the underlying causes for differences in predictions by DUROS+ and XBeach. As both models are based on laboratory experiments, differences in laboratory experiments on various scales are analysed and simulated with both models. Testing the models with the experiments involves both calibration and validation.
Scaling relations were found to form the base for the experiments: scaling relations were used to create pre-storm profiles in laboratory from the (prototype) reference case. The relations were gathered by relating the erosion amounts on various scales from earlier experiments. The correctness of these relations needs to be considered and validated with the experimental results.

1.4 Research approach and outline

The empirical DUROS-model, which is presently used for the safety assessment of dunes, predicts a different storm impact than the process-based XBeach-model, for normative storm surge conditions. The discrepancy between the results of the DUROS-model and the XBeach-model on prototype scale leads to the following research questions with respect to the model performance:

<u>Research questions:</u>
What causes the difference in storm impact predicted by DUROS and XBeach for reference conditions?

And,

What consequences do these differences in storm impact have on the prediction for prototype scale?

In order to answer the research questions, they were divided in different questions that arise when analysing the research questions in more detail:

1) *To what extent do erosion processes differ on various laboratory scales?*

2) *To what extent can the scaling rules be used to relate sediment transport and accompanying dune erosion on various laboratory scales?*

3) *How sensitive are the model results for varying boundary conditions?*

4) *To what extent are the models capable of simulating dune erosion on various lab scales and what model settings have to be changed to improve the performance?*

5) *To what extent can the dune erosion models be used to simulate erosion on prototype scale?*

The questions are discussed in five chapters; literature study, experimental analysis, model description and sensitivity, model performance on lab and model performance on prototype. Each chapter starts with a research methodology and a chapter outline.

Approach to research questions and outline
Chapter 2
Starting with literature, the aspects of dune erosion that are relevant for this research are discussed. The terminologies of the coast that are used throughout the report are described (section 2.2). In section 2.3 the processes involved with dune erosion are qualitatively described. In order to compare the models, impact- and error indicators have to be defined (section 2.4). They were used to quantitatively describe the model performance. Error indicators describe variance in measurements. The previous mentioned scaling rules are discussed in detail to clarify the accuracy of this distortion relation (section 2.5).

Chapter 3
The dune erosion models were constructed with the results of several laboratory experiments on various lab scales. The fact that both models are based on similar experiments and perform differently on prototype implies that either processes on various scales are not integrated sufficiently in the models or the lab-prototype conversion is differently. An analysis of the laboratory experiments should discover which processes are dominant for dune erosion (section 3.2 and 3.3).
As the scaling rules form the base for the experiments, they should also be used to relate the transport rates in the experiments. In section 3.4 they were tested with the experimental results. The idea of analysing the laboratory experiments before simulating the experiments with the models is to verify whether the experimental data contains certain similarities and differences and need to be considered when evaluating with the models.

Chapter 4
In this chapter, the DUROS-model (section 4.2) and the XBeach-model (section 4.3) are described, with the aim of a better understanding of the model concepts; their background, their

purpose and their way of performing. The two models differ in concept as DUROS is empirically deduced and XBeach is process based. The applicability of the models in directly related to their approach. Their way of performing is examined through a sensitivity analysis of the models to varying boundary conditions (section 4.4).

Chapter 5
In chapter 5, the DUROS-model (section 5.2) and the XBeach-model (section 5.3) will be evaluated with laboratory experiments on various scales. As the models are constructed with the results of these laboratory experiments, they are expected to perform very well when simulating the experiment. Earlier research showed (not published) that the model performance of both models declines for smaller experiments. In section 5.3, the XBeach-model is calibrated and validated with the experiments on various scales. It is hypothesised that when a model performs comparable on various laboratory scales, the model performance is similar on prototype scale.

Chapter 6
For safety assessment, the models are compared on prototype scale. The comparison of Van Thiel De Vries (2009) showed differences in storm impact prediction for the present DUROS and process-based models. Results from the previous chapters were used to adjust the XBeach-model settings. The calibration of the new model is performed with the insight from the analysis of the experimental data (C-3), the model sensitivity (C-4) and the model verification with lab experiments (C-5). In this chapter the models are compared on prototype scale. For this purpose the performance for the 'reference case' (section 6.2) and some field data from the '76 storm (section 6.3) was analysed. The outline of the research framework is shown in figure 1.2.

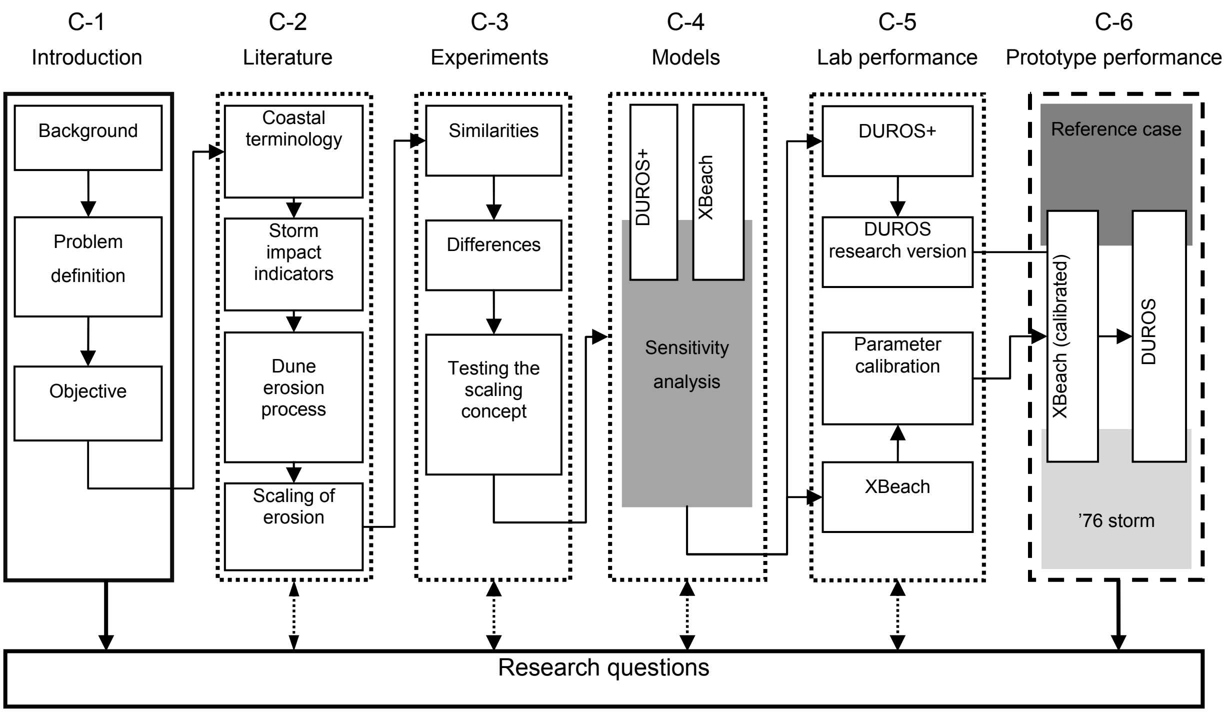


Figure 1.2: Outline of the research framework.

Chapter 7
The last chapter provides the conclusions and recommendations. With the results of chapters 2-6 the research questions can be answered. Afterwards, recommendations for (possible) further research are given.

2 Literature study

2.1 Introduction

In this chapter the aspects of dune erosion that are relevant to this research are described. In the first section the coastal terminology used in this thesis is explained. In section 2.3, the dune erosion process is described qualitatively. From the qualitative description the scaling rules of Vellinga (1986) are deduced (section 2.4). In the last section, the chosen model performance indicators are discussed. The indicators are used to quantify the performance of dune erosion models. Models that have highest performance are consequently the best performing models.

2.2 Coastal terminology

In this report several references are made to various definitions that describe the coastal zone (see figure 2.1). The coastal zone describes the transition area from water to land. This zone extends from offshore until the last point that is affected by storm surges. This last point is the coastline, i.e. the intersection of a certain water level and the land. The dune foot is defined as the first bend in the profile above storm surge level. The position of the dune foot can therefore change in time. The nearshore, or shoreface, is the area between the beach and the start of wave breaking. Two types of wave breaking can be distinguished, bar breakers and shore breakers. Broken waves propagate through the near shore in what is called the surf zone. The swash zone is the area of the beach that lies between maximum wave run-up and rundown (United states Army Corps of Engineers, 2002).

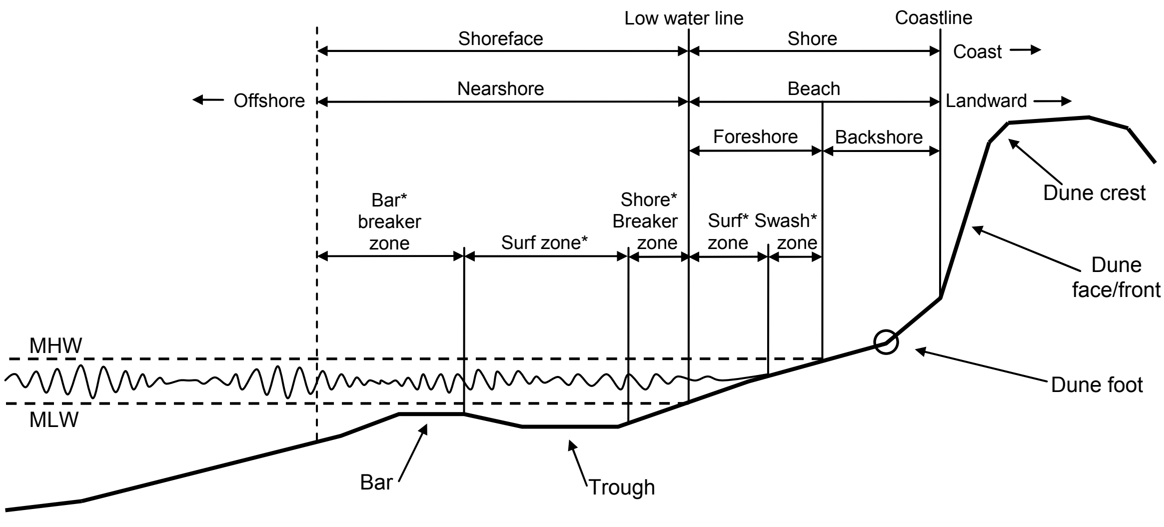


*Figure 2.1: Definition of near shore areas (United states Army Corps of Engineers, 2002). *Location and width vary as the wave conditions change.*

2.3 The process of dune erosion

Dune erosion is the result of the resistant forces of the dune in terms of soil mechanic properties and the hydraulic transport capacity of waves and currents. During a storm surge, the beach profile continuously adjusts to the hydraulic and meteorological conditions. During the passage of a low-pressure field across the North Sea in Southeast direction, strong winds are generated initially from Southwest to Northwest direction. Together with the tidal effect, such storms cause a sea level rise of several meters and wave heights up to 5-8 meters at the Dutch coast. Because of the rise of the sea level, the waves will reach the front of the dunes.

Initially, the wave energy is dissipated over a very short distance, as the dunes and the beach just in front of it are relatively steep. Consequently, relatively high waves break in relatively shallow water. The breaking waves ‘hit’ the bottom and large quantities of sediment are stirred up. The larger part of the suspended sediment settles further seaward in a less turbulent environment so that the beach just in front of the dunes lowers.

After a number of waves, the foot of the dune is eroded to such extent that the dune front becomes instable. Then, a slice of sand slides down forming a pile of sand at the foot of the dune. This volume of sand is then gradually eroded by the waves. When waves have cleared away the pile of sand a new dune front instability occurs. Because of the further seaward settling of suspended sediment the beach is elevated. The slope of the beach becomes gentler, the energy is dissipated over a broader distance and consequently the offshore transport decreases. This process would continue until a new equilibrium beach profile is formed corresponding to the storm surge sea level, according to Bruun (1954), Dean (1977), Vellinga (1986) and Steetzel (1993). As the response of the coast to the fast changing hydrodynamic conditions is relatively slow, such equilibrium state won’t be reached during a storm surge.

Based on the observations and interpretations it is assumed that the erosion of the dunes is fully controlled by the sediment transport capacity of the breaking waves and that the resistant forces are relatively unimportant to the rate and quantity of dune erosion (Vellinga, 1986). In figure 2.2, an example of a schematized interaction of coastal processes is shown.

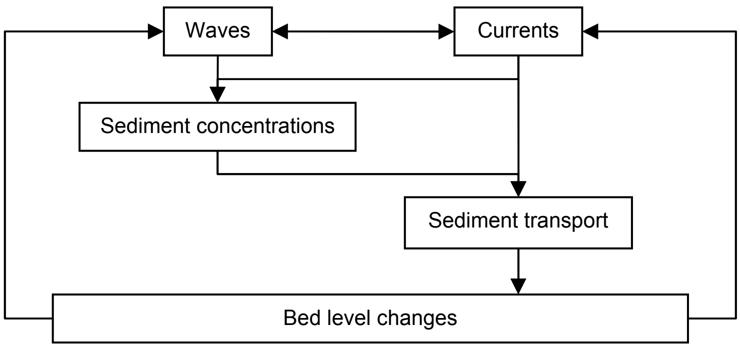


Figure 2.2: Interaction of coastal processes in a process-based model (SBW-Duinen2, 2008).

2.4 Scaling rules

In order to be able to simulate dune erosion on laboratory scale, the conditions on laboratory scale and the conditions on prototype scale need to have a certain similarity. Hughes (1993) describes this as the concept of similitude. Ideally, a properly designed laboratory model should behave in all respects like a controlled (usually miniature) version of the prototype. In a sediment model, this similar behaviour includes the velocity, acceleration and mass transport of sediment and the resultant forces of the fluid, in which the sediment is, exerts on the sediment (Hughes, 1993).
Similitude is achieved when all major factors influencing reactions are in proportion between prototype and model, while those factors that are not in proportion throughout the model domain are so small as to be insignificant in the process (Hughes, 1993).

The dune erosion model (DUROS) was constructed using scaling rules to relate profiles in laboratory and profiles on prototype scale. Vellinga (1986) distinguishes three steps in which a transition is made from prototype to laboratory by:

- Geometric scaling according to Froude*,

- Steeping of the profile due to smaller sediment sizes*,
- Additional steeping due to limited dimensions of the wave flume.

*The first two steps together are the distortion relation of Vellinga (1986).

The different steps are parameterized in morphologic scale parameters, fall velocity (n_{ws}) and the average sediment size (D_{50}), hydrodynamic parameters, wave height (n_H) and wave period (n_T), the spatial parameters, length scale (n_l), depth scale (n_d) and steepness factor (St_f) and the temporal parameter, the morphological time scale (n_{Tm}).

Step 1: Geometric scaling according to Froude

In this step, the laboratory profile is geometric scaled until its elevation resembles the prototype elevation. The profiles are scaled according to the concept of dynamic similarity described by the Froude number and geometric similarity due to the dimensionless fall velocity. The (depth) scale parameter n_d is defined as d_p/d_m with d_p=parameter value for the depth on prototype and d_m=parameter value on laboratory scale.

To maintain a dynamic similarity the Froude number, equation (2.1), needs to be the same in prototype and laboratory, thus

$$\left(\frac{V}{\sqrt{gl}}\right)_{prototype} = \left(\frac{V}{\sqrt{gl}}\right)_{laboratory} \tag{2.1}$$

With V the characteristic velocity, the acceleration due to gravity g and the characteristic length l. Expressing this relation in terms of scale ratios,

$$\frac{n_V}{\sqrt{n_g n_l}} = 1 \tag{2.2}$$

Because the gravitational force is the same in lab and prototype, n_g=1, such that equation (2.2) can be rewritten as

$$n_V = \sqrt{n_l} \tag{2.3}$$

Combining linear wave equations and the Froude relations, results in:

$$n_L = n_H = n_d = n_x \tag{2.4}$$

$$n_t = n_T \tag{2.5}$$

In which n_x is the horizontal length scale factor (comparable with n_l), the wave height scale factor n_H, time scale factor n_t, and n_T the wave period scale factor. Parameters L (wave length), d, and T (wave period) are dependent on wave motion. Their interrelation can be described by the dispersion relation (Vellinga, 1986):

$$\left(\frac{2\pi}{T}\right)^2 = \frac{2\pi g}{L}\tanh\left(\frac{2\pi d}{L}\right) \tag{2.6}$$

Combining (2.4) and (2.5) according to relation (2.6), the next relation for dynamic similarity according to Froude scale is gathered:

$$n_H = n_L = n_d = n_T^2 = n_t^2 = n_u^2 = n_v^2 \quad (2.7)$$

With n_u and n_v, the horizontal flow velocity scale factor in resp. x and y-direction. According to Kemp and Plintson (1968), Noda (1972), Dalrymple and Thompson (1976) and Gourlay (1980), dynamic similarity (undistorted beach profiles (n_l=n_d)) can only be obtained when the dimensionless fall velocity (ratio between the orbital velocity and the fall velocity of grains) stays the same. Scaling of the dimensionless fall velocity parameter is done by:

$$n\left(H/Tw_s\right) = 1 \quad (2.8)$$

Using the Froude scale (2.7), the fall velocity is related to the depth by:

$$n_{ws} = n_d^{0.5} \quad (2.9)$$

The first scaling step is performed according to relation (2.7) and (2.9). Applying them on the original data set results in a new profile, wave height, wave period and sediment size.

<u>Step 2: Steeping of the profile due to smaller sediment sizes</u>

If the prototype sediment size is 200µm, to keep a dynamic similarity on the laboratory scale, the sediment size will become smaller than 100µm (dependent on the scale factor). With sediment fractions lower than 100µm, the Reynolds criterion will not be met and cohesive forces will become dominant. To prevent this effect, sediment sizes in laboratory have to be increased. To maintain the same relation between sediment transport in prototype and laboratory scale, a steeping of the profile is proposed to undo the effect of sediment size difference. After all, smaller sediment size goes with less friction between two moving sand layers that results in bed instability.

Le Mehaute (1970) states the kinematical similarity, the ratio between orbital velocity (~H/T) and the fall velocity (w_s), has to be the same in lab and prototype scale. When sediment sizes become too small, steeping the profile should be done according to the distortion relation:

$$n_l / n_d = n_u / n_{ws} \quad (2.10)$$

Implementing Froude scale in relation (2.10), results the distortion formula:

$$n_l / n_d = \left(n_d / n_{ws}^2\right)^{0.5} \quad (2.11)$$

Vellinga (1986) proposed a different distortion relation. He based the profile distortion on the scaling of the sediment transport that is discussed below.

Distortion relation from scaling sediment transport

The horizontal velocity of sediment grains as a function of time and position (u_g) and the sediment concentration as a function of time and position (c) determine the sediment transport per unit width (S_x), with the relation:

$$S_x(t) = \frac{1}{t}\int_0^t \int_0^{\eta(t)} c(z,t)\,u_g(z,t)\ \mathrm{dz\ dt} \quad (2.12)$$

With η(t)=elevation of the water surface as a function of time and position.

To simplify relation (2.12), the variation of the sediment concentration with time is assumed to be small compared to the time-averaged concentration. The assumption implies that the contribution of the time-averaged velocity to the sediment transport is an order of magnitude larger than the contribution of the asymmetry of the wave motion (Vellinga, 1986). So relation (2.12) is approximated by:

$$S_x = \int_0^{\bar{\eta}} \bar{u}(z)\bar{c}(z)\ \mathrm{dz} \qquad (2.13)$$

The over-bar denotes time-averaging with an averaging time based on the lowest frequency of the signal (the actual wave period) (Steetzel, 1993).
Waves induce successively onshore (by the wave crest) current and offshore (by the wave through) current. Therefore, the induced sediment transport can be divided in onshore and offshore:

$$S_x = \int_0^{\bar{\eta}_1} \bar{u}(z)\bar{c}(z)\ \mathrm{dz} - \int_{\bar{\eta}_1}^{\bar{\eta}} \bar{u}(z)\bar{c}(z)\ \mathrm{dz} \qquad (2.14)$$

In which the boundary is fixed at the wave through level $\bar{\eta}_1$.
The continuity of the water volume, leads to a time-averaged water flow rate in the vertical plane (q_{ret}).

$$S_x = q_{ret}\left(\int_0^{\bar{\eta}_1} \bar{c}(z)\ \mathrm{dz} - \int_{\bar{\eta}_1}^{\bar{\eta}} \bar{c}(z)\ \mathrm{dz} \right) \qquad (2.15)$$

Relation (2.15) can be rewritten as:

$$S_x = q_{ret}\left(c_2 - c_1\right) \qquad (2.16)$$

When the velocity field can be reproduced according to Froude, the time-averaged water flow rate can be described in term of velocity and depth:

$$n(q_{ret}) = n_d n_u = n_d^{1.5} \qquad (2.17)$$

$$n_{c1} = n_{c2} = n_c \qquad (2.18)$$

Relation (2.16) can now be rewritten to:

$$n\left(S_x\right) = n_d^{1.5} n_c \qquad (2.19)$$

The degree of turbulence, the rate of energy dissipation and the potential energy of sediment are assumed to be related (Vellinga, 1986). The wave energy flux (2.25) dissipates in the surf zone per unit length (Δx) and per unit width (Δy), resulting in an energy dissipation rate:

$$\text{Energy dissipation rate} = \frac{\partial E c_g \Delta x \Delta y}{\partial x} \tag{2.20}$$

If sediment particles settle to the bottom, the lost potential energy is:

$$\frac{\partial mgz}{\partial t} = mgw_s \tag{2.21}$$

The suspension of solids in a fluid is described by the non-stationary, diffusion equation according to:

$$\frac{\partial C}{\partial t} = w_s(z)\frac{\partial C}{\partial z} + \frac{\partial}{\partial z}\left(\varepsilon_s(z)\frac{\partial C}{\partial z}\right) \tag{2.22}$$

In order for sand to maintain its potential energy (first term in (2.22)), that is otherwise lost to kinetic energy due to gravity (second term), it needs to 'consume' energy (third term eq. (2.22)). This energy consumption relates to the energy dissipation of waves:

$$mgw_s \sim \frac{\partial\left(Ec_g\right)\Delta x \Delta y}{\partial x} \tag{2.23}$$

With m is the total mass of the particles in suspension:

$$m = c\rho_s \Delta x \Delta y d \tag{2.24}$$

And the wave energy flux Ec_g:

$$Ec_g = \frac{1}{8}\rho g H^2 c_g \tag{2.25}$$

Combining relation (2.24) and (2.25) with (2.23) yields in an expression for the sediment concentration in a turbulent flow:

$$c\rho_s \Delta x \Delta y d g w_s \sim \frac{\partial\left(\frac{1}{8}\rho g H^2 c_g\right)\Delta x \Delta y}{\partial x} \tag{2.26}$$

The scale factor for the sediment concentration can be described, using Froude relation ($n_H = n_d = n^2_{cg}$):

$$n_c = n_d^{1.5} n_l^{-1} n_{ws}^{-1} \tag{2.27}$$

Inserting this in relation (2.19), yields:

$$n\left(S_x\right) = n_d^3 n_l^{-1} n_{ws}^{-1} \tag{2.28}$$

By definition, the scale factor for sediment transport is equal to the scale factor for the rate of change of volume n_A (Vellinga, 1986). For two-dimensional conditions, this yields:

$$n\left(S_x\right) = n_A / n_t = \left(n_d n_l\right) / n_t \tag{2.29}$$

Combining (2.28) with (2.29), results in:

$$n_l / n_d = \left(n_t / n_{ws}\right)^{0.5} \tag{2.30}$$

When the morphological time scale factor (n_{Tm}) equals the hydraulic time scale factor (n_t), relation (2.30) yields:

$$n_l / n_d = \left(n_d^{0.5} / n_{ws}\right)^{0.5} = \left(n_d / n_{ws}^2\right)^{0.25} \tag{2.31}$$

Vellinga and van de Graaff found the almost identical scale relation:

$$n_l = n_d \left(\frac{n_d}{n_{ws}^2}\right)^{0.28} \tag{2.32}$$

In case of similar sediment property (n_{ws}=1), relation (2.32) becomes:

$$n_l = n_d^{1.28} \tag{2.33}$$

The first two scaling steps are based on this distortion relation. In the first step, the profiles were undistorted scaled. Therefore, the second scaling step is gathered by:

$$n_l = n_d^{0.28} n_{ws}^{-0.56} \tag{2.34}$$

Step 3: Additional steeping due to limited dimensions of the wave flume

The purpose of scaling is simulating prototype conditions correctly in dune erosion experiments conducted in laboratory. Limiting factors in this transition are the available sediment sizes and the dimensions of the test facility (in the case of Vellinga; the Wind- and Deltaflume). In order to prevent scale effects becoming important in sediment transport, the downscaling has to be limited. Due to this, the profile in laboratory gets an extra steeping to suit for the limiting dimensions of the Deltaflume. The profile was multiplied with a steepness factor St_f:

$$n_l' = n_l * St_f \tag{2.35}$$

2.5 Model performance indicators

To quantify the model performance of the two dune erosion models, two types of indicators can be used. The first type concerns impact indicators and give insight in the storm impact on a coastal profile. The second type concerns model errors in relation to measurements.

2.5.1 Impact indicators

Profile development

During a severe storm surge event the shape of the coastal profile changes as a result of offshore directed sediment transport. The observations that characterize profile development are e.g. the offshore spreading of sediment, the beach height, the beach slope and the dune foot height, and are used to qualitatively assess the model performance. It should be considered that all these characteristics are very irregular in time and strongly dependent of periodically sliding of sediment from the dune to the beach. E.g. the beach height in front of the dune before and after a periodically sliding can vary up to 2 meters (on prototype scale).

Erosion volume

During a storm sand is eroded from the dunes to build up a new foreshore. Storm impact on dune systems is frequently described by the erosion volume. The erosion volume is defined as the dune volume loss as a result of offshore sediment transport during extreme storm conditions. Two types of erosion volumes can be distinguished; erosion volume above the maximum storm surge level and total erosion volume (see figure 2.3). Within Dutch legislation, the erosion volume is the integral between pre-storm ($z_{b,0}$) and post-storm profile ($z_{b,m}$) above the maximum storm surge level (SSL), as defined by the formula:

$$\text{Erosion volume} = \int_{SSL}^{dunetop} (\text{intial profile - post storm profile})\,dz \qquad (2.36)$$

For ($z_{b,0}$) ≥ ($z_{b,m}$)

In this study, the above formula is used to quantify the dune erosion amount.

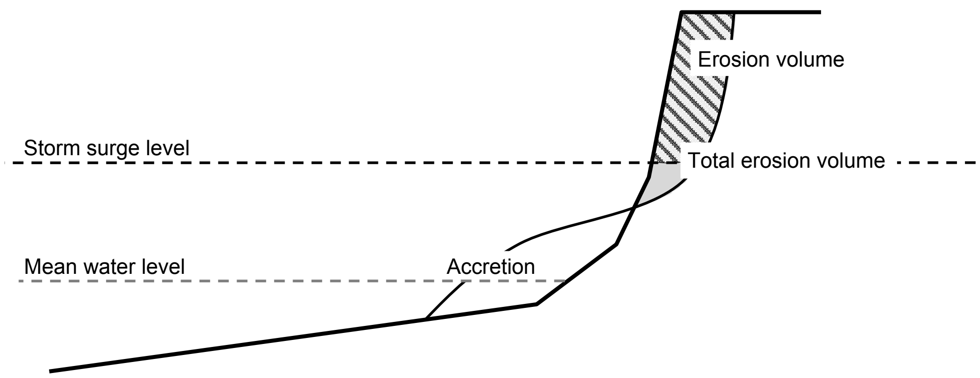


Figure 2.3: Erosion volume definition according to VTV2006. The thick solid line is the reference profile.

Dune retreat

The dune retreat is the horizontal distance between the initial dune front and the post-storm dune front:

$$\text{Dune retreat} = \left| x_{0,dunefront} - x_{t,dunefront} \right| \qquad (2.37)$$

The retreat is chosen to be computed at +12 N.A.P. The dune retreat is an important measure for Coastal Zone Management (CZM) (e.g. the dune retreat is relevant for the safety of constructions/buildings near and within the dune zone).

2.5.2 Error indicators

Correlation coefficient

The correlation coefficient (or cross-correlation) *r* is a quantity that gives the quality of a least squares fitting to the original data. So, the correlation coefficient for two exactly similar data sets is *r*=1 and decreases with more scatter around the trend. The correlation coefficient is defined as:

$$r = \frac{ss_{xy}}{\sqrt{ss_{xx} ss_{yy}}} \tag{2.38}$$

With ss_{xx} and ss_{yy} the sum of squares values and ss_{xy} the sum of squares residuals about their means. With:

$$ss_{xx} = \sum_{i=1}^{n} (X_i - \overline{X}_i)^2 \tag{2.39}$$

$$ss_{yy} = \sum_{i=1}^{n} (Y_i - \overline{Y}_i)^2 \tag{2.40}$$

$$ss_{xy} = \sum_{i=1}^{n} \left(X_i - \overline{X}_i \right)\left(Y_i - \overline{Y}_i \right) \tag{2.41}$$

In which $\overline{X}$ and $\overline{Y}$ are the sample means of the set of *n* data points (X_i , Y_i).

Brier Skill Score

Sutherland et al. (2004) analysed different error measurement methods for evaluating the performance of morphological models. In this study, on behalf of comparing the morphological models the performance is expressed in three criteria, the bias, the accuracy and the skill of a model. The Brier Skill Score method of van Rijn et al. (2003) (equation (2.42)), that compares predicted ($z_{b,c}$) and measured profile ($z_{b,m}$) with the initial profile ($z_{b,0}$) and adjusting it for the measurement error δ (assumed to be zero), appears to be the most suitable method for this purpose.

$$BSS_{vR} = 1 - \frac{\left\langle \left(\left| z_{b,c} - z_{b,m} \right| - \delta \right)^2 \right\rangle}{\left\langle \left(z_{b,0} - z_{b,m} \right)^2 \right\rangle} \tag{2.42}$$

The Skill Score provides an objective method for assessing the performance of morphological models. The alternative classification of Van Rijn et al. (2003) is used. It was chosen to apply the BSS-method to the entire profile (so; not only the active part of the profile).

	BSS_{vR}	**BSS**
Excellent	1.0 - 0.8	1.0 - 0.5
Good	0.8 - 0.6	0.5 - 0.2
Reasonable/fair	0.6 - 0.3	0.2 - 0.1
Poor	0.3 - 0.0	0.1 - 0.0
Bad	< 0.0	< 0.0

Table 2.1: Classification table for the Brier Skill Score (Sutherland et al. 2004).

3 Experimental data

3.1 Introduction

In the late eighties the Dutch government assigned WL|Delft Hydraulics (now Deltares), to develop a dune erosion prediction model for the Dutch coast. This research program (M1263) consisted of large amounts of small-scale and large-scale laboratory experiments, that provided sufficient knowledge about dune erosion to develop a simple dune erosion model, DUROS (Vellinga, 1984). In 2009, Deltares was assigned to review the former model and to develop a new dune erosion model (DUROS**++**), combined in the research program SBW-Duinen. A digitalization of the report series M1263 was performed within this research program. For the development of DUROS++ only profile measurements (z_b) were digitized. Table 3.1 below provides a brief summary of the experiments that were used. These measurements are also used in this study.

	Research program	Number of experiments	Scale (n_d)	D50 (µm)	Data	References
Large-scale Delta flume	M1263-III	3	5	225	z_b, H_s*	WL|Delft Hydraulics (1984)
Small-scale Wind flume	M1263-I	17	26-84	225	z_b, H_s*	WL|Delft Hydraulics (1976)
	M1263-II	6	26-84	225	z_b, H_s*	WL|Delft Hydraulics (1981)

*Table 3.1: Available 1D laboratory experiments for model calibration and validation. The profile measurements (z_b) are provided from the SBW-research program. *Measured wave heights (H_s) were extracted from the M1263-reports.*

In this chapter, the next research questions are evaluated:

1) ***RQ-1*** *To what extent do erosion processes differ on various laboratory scales?* (section 3.3), and
2) ***RQ-2*** *To what extent can the scaling rules be used to relate sediment transport and accompanying dune erosion on various laboratory scales?* (section 3.4).

The experimental results of the M1263 project are analyzed, because they are the base for the models. The purpose of the data analysis is to obtain insight in the experimental characteristics that could be important for model calibration and evaluating model performance. Similarities in post-storm profiles were investigated and the influence of the hydrodynamics (wave period and wave height) and the morphologic parameters (the initial profile and the grain size) on the sediment transport was analyzed.
In section 3.2, the laboratory profiles on the same scale are compared. Vellinga (1986) stated that in experiments with the same hydrodynamic conditions the profiles develop to a comparable post-storm profile which is not dependent of the initial profile. In section 3.3 laboratory profiles on different scales are compared: 1) the duration, until an equilibrium state will be reached, 2) the slope in the run-up zone, 3) the run-up height and 4) the shape of the post-storm profile are discussed.
In section 3.4, the differences between the laboratory profiles on different scales are compared with scale relations discussed in chapter 2.

3.2 Comparison of laboratory profiles on the same scale

Profile measurements are available from 26 different experiments (see table 3.1) all conducted with approximately the same sediment properties (D_{50}=225μm). The experiments differ in the depth and length scale, initial profile and the applied hydrodynamic conditions. The pre-storm and post-storm profiles are sorted by depth scale and plotted in figure 3.1.

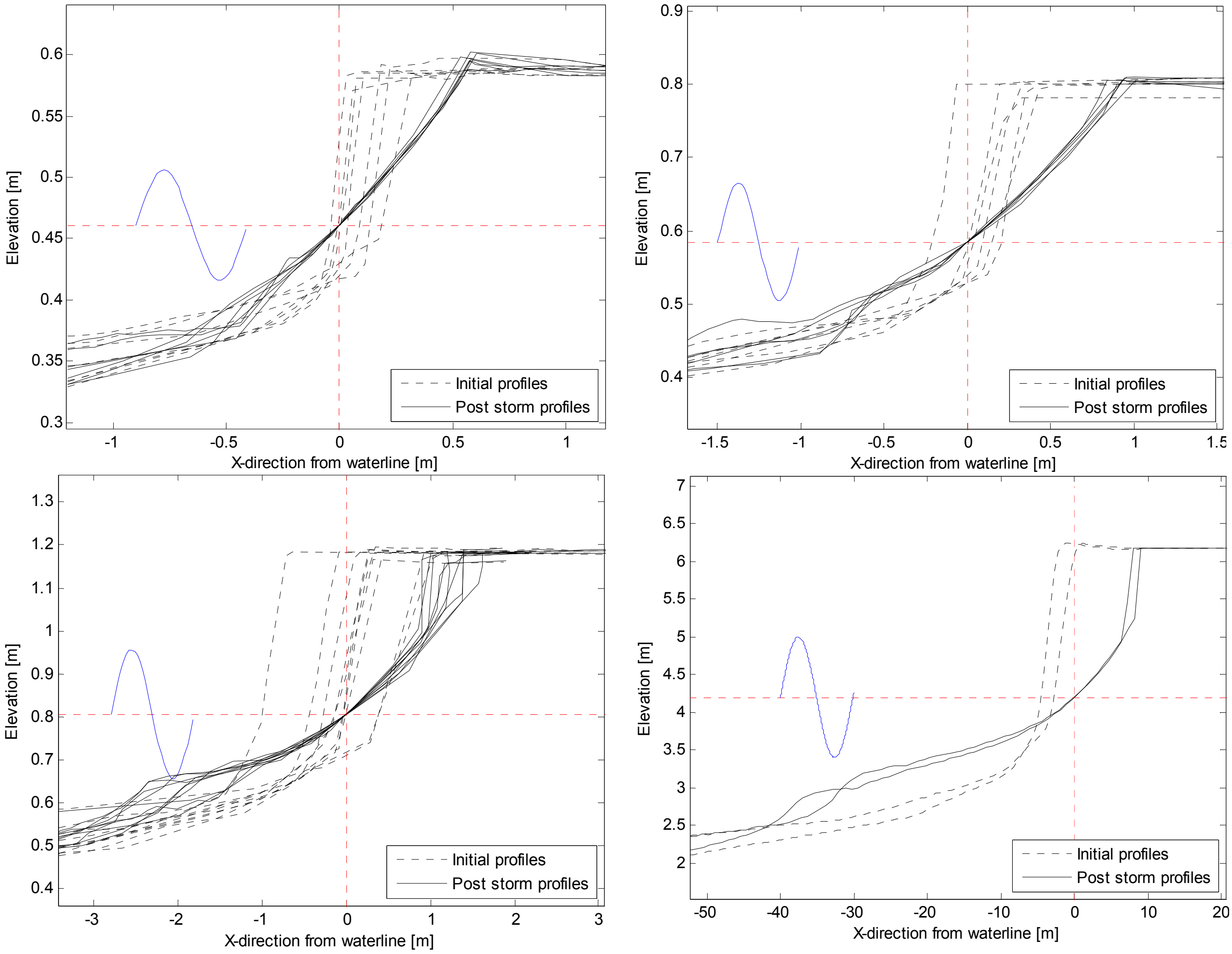


Figure 3.1: The similarity of experiments on the same scale with D_{50}=225μm. The sinusoidal function indicates the wave height (Hs) at the wave board. The solid lines are the post-storm profiles, the dotted lines are the initial profiles. Upper left panel: Laboratory experiments on scale n_d=84. Upper right panel: Laboratory experiments on scale n_d=47. Lower left panel: Laboratory experiments on scale n_d=26. Lower right panel: Laboratory experiments on scale n_d=5.

To compare the profiles from different tests, the intersection of the post-storm profiles with the water line was chosen to be the reference point for each experiment. This point was subsequently horizontally shifted to x=0m (pre-storm profile were shifted over the same distance). In figure 3.1, for each experiment the initial profile and the last measured profile are plotted. The experiments vary in simulation time, the hydrodynamics (wave period (T_p) and wave height (H_s)) and the initial profile.

As can be observed, the variation between different initial profiles horizontal but also in vertical direction (offshore) is relatively high compared to the variance between measured post-storm profiles (see figure 3.1). Therefore it can be stated: the profiles for experiments on the same scale show comparable post-storm profiles independently of pre-storm profiles.

Variance in post-storm profiles

Differences in the post-storm profiles are partly caused by the variation in the hydrodynamic conditions during the experiments. The wave height in the experiments varies from 6,9m to 8,3m (prototype) on scale n_d=84, from 7,2m to 8,1m on scale n_d=47, from 7,2m to 7,8m on scale n_d=26 and from 8,0m to 8,3m on scale n_d=5. Also the wave period on scale n_d=26 and scale n_d=47 vary resp. from 9s to 12s and from 12s to 16s. The wave period is assumed to have a strong correlation with the run-up height (see section 3.3). The large variation in the experiment duration also contributes to the difference between the experimental post-storm profiles. Other variations can be explained by measurement inaccuracy and complications with experimental set-up (e.g. the ratio between wave climate and water depth).

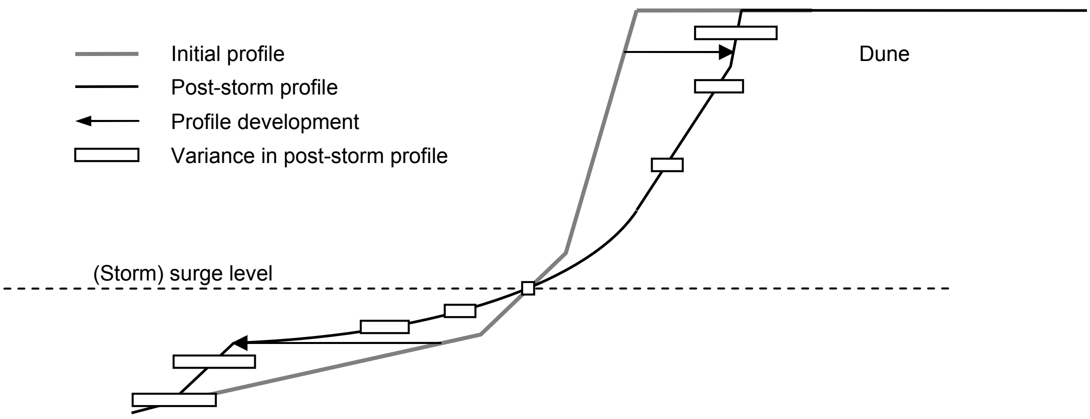


Figure 3.2: Schematized profile development in laboratory.

Vellinga (1986) stated for experiments with the same hydrodynamic conditions, the profile developments, e.g. the simulated post-storm profiles in the laboratory are comparable and independent of the initial profiles. This can partly been confirmed when relating the observed variance in post-storm profiles to the total profile development during an experiment. The statement is valid for -3m (prototype) until the dune foot. The high variation offshore indicates that the influence of the initial profile cannot always be ignored.

3.3 Comparison of laboratory profiles on different scales

Profile evolution in time

The (distorted) reference profile applied in the laboratory represents an average equilibrium profile for normal hydrodynamic conditions for the Dutch coast. During a simulated storm surge the hydrodynamic conditions vary, which results in an in general more gentle coastal profile at the shore. As the experiment proceeds, the coastal profile adapts to the new hydrodynamic conditions by a redistribution of the coastal sediment. The duration of the development of a new (quasi-) equilibrium profile is not the same for all lab scales. The erosion rate near an equilibrium state approaches zero, therefore the erosion rates (that are linked to the erosion volumes) were used to map the profile development for each scale. Table 3.2 gives an overview of the cumulative erosion volumes for each depth scale.

A trend in profile development can be distinguished in the table 3.2: small-scale experiments reach a quasi-equilibrium state (t_{eq}) quicker than large-scale experiments. If the equilibrium is assumed to be reached if ~95% of the total erosion volume has eroded (see figure 3.3), an equilibrium condition occurs after approximately 3hour for depth scale n_d=84 and >10hours for depth scale n_d=5.

Depth scale	<0.2h	<0.5h	<1.0h	<3.0h	<6.0h	<10.0h	>10h
84	65	75		95	100		
47		55	75	85		100	
26		50	65	75		100	
5	10	25		45	75	90	100

Table 3.2: The cumulative measured erosion volume in [%] above storm surge level (averaged per depth scale). Empty cells are either no measurement or less than two measurements.

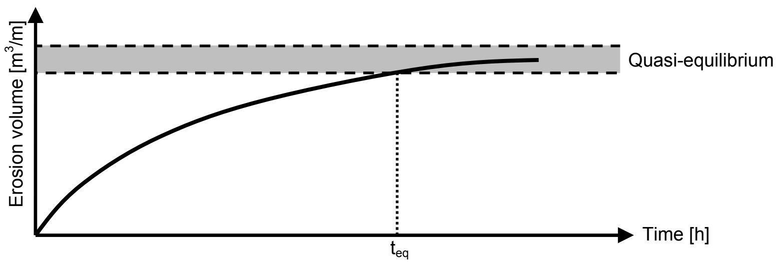


Figure 3.3: Schematized development of a quasi-equilibrium state.

The small difference in measured profiles ($t_{measured}$>0.5h) on scales n_d≥26 shows that (quasi) equilibrium has already been reached (see figure 3.4). One remark here is that this observation could not be proved because the measurement time interval on small scales and the duration of the experiment are very limited.

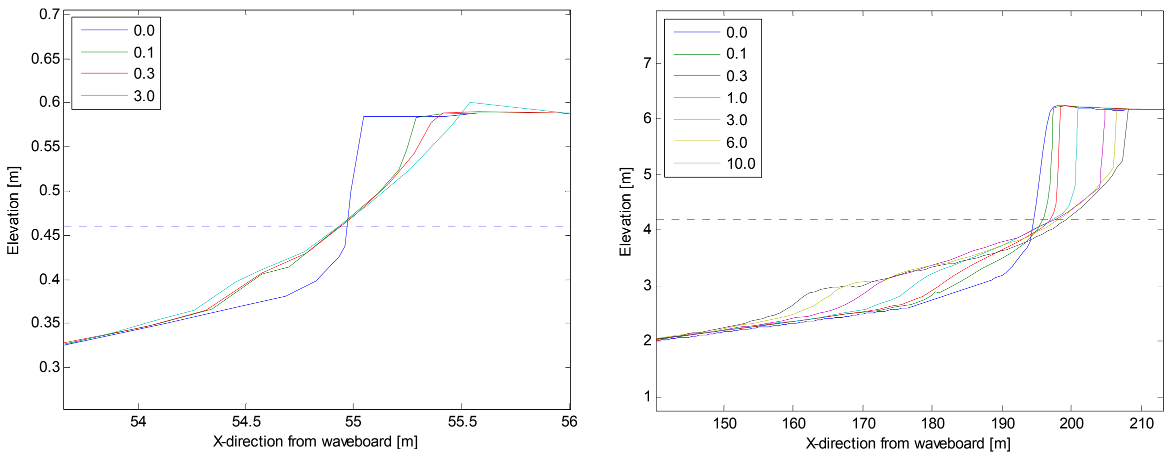


Figure 3.4: Profile development in laboratory. Left panel: Small-scale experiment CT63 (n_d=84) with profile measurements at t= [0.0 0.1 0.3 3.0] hours. Right panel: Large-scale experiment test-1 (n_d=5) with measurements at t= [0.0 0.1 0.3 1.0 3.0 6.0 10.0] hours.

Unlike small scale experiments, in large scale experiments (n_d<26) an ongoing retreat of the dune front is observed as the experiment proceeds. It is therefore assumed that equilibrium has not been reached in these large-scale experiments.

Slope at the dune (-face)

Experiments on the same scale result in a comparable slope in the run-up zone. The run-up zone is bound from the water level until the dune foot. The run-up slope is assumed to be dependent on the foreshore slope, the supply of sediment by the dune (S_{dune}) and the transport capacity of the near-shore hydrodynamics (S_{hydro}). The foreshore slope is dependent on the sediment characteristics and the near-shore hydrodynamics.

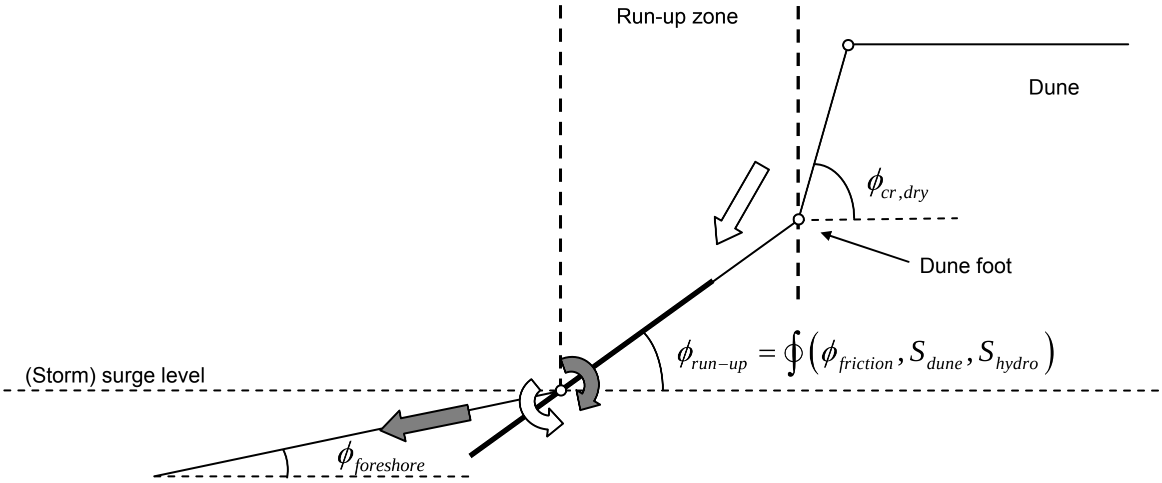


Figure 3.5: Run-up zone: The slope at the dune face is assumed to be a function of the foreshore slope of sediment and the supply/demand ratio in the run-up zone. The white arrow is the supply of sediment from the dune as a result of the sliding down of sediment. The increase of sediment in the run-up zone results in a steepening of the run-up slope. The gray arrow represents the transport capacity of sediment and its effect on the run-up slope.

Figure 3.5 indicates that a supply of sediment results in a steeping of the run-up zone (white arrows). Flattening of the run-up zone will occur when the demand exceeds the supply of sediment (often observed near a static dune protection, like a revetment).
The run-up slope is not the same for different experiment scales. The average slopes for each depth scale are extracted from the experimental data and listed in table 3.3.

Depth scale	ϕ_{run-up} [-] (D_{50}=225μm)	ϕ_{run-up} [-] (D_{50}=150μm)	ϕ_{run-up} [-] (D_{50}=95μm)
84	0.21	0.21	
47	0.19	0.19	
26	0.17	0.16	0.14
5	0.11		

Table 3.3: The run-up slope per depth scale (extracted from laboratory experiments M1263). The second and third columns represent the run-up slopes for other sediment sizes. The empty cells indicate that no experiments were done with these characteristics.

The run-up slopes are almost two times higher for small scale experiments than for large scale experiments. The slopes in experiments with other grain sizes are quite similar to the experiments with D_{50}=225μm. The differences in (run-up) slopes cannot be explained, but they are expected to be important and should be considered while evaluating the models' performance.

Vertical position of the dune foot: wave run-up height

Comparing the experiment results on different scales, a clear distinction between run-up heights can be observed. During the small-scale experiments, the run-up heights have been measured and plotted in Figure 3.6. Run-up heights in the large-scale experiments were extracted from the profile measurements (assuming that waves run-up till the dune foot).

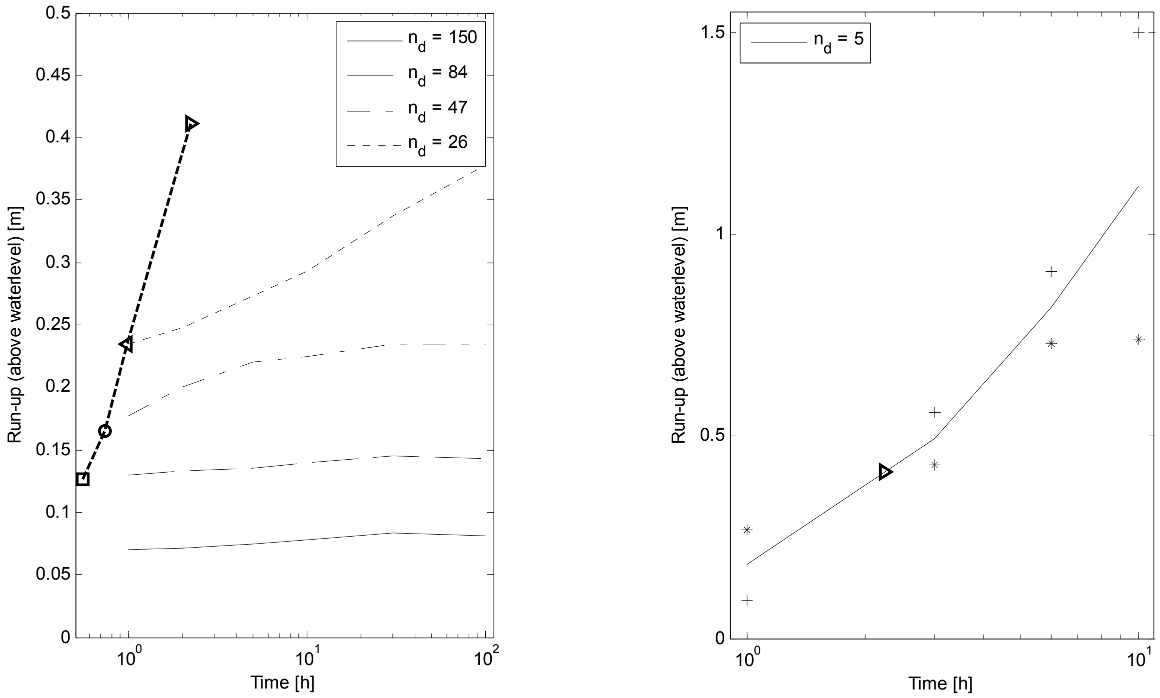


Figure 3.6: The wave run-up (in lab) as a function of time. Left panel: Run-up heights extracted from M1263 report (FIG. 156). Right panel: The average run-up heights from Test-1 (plus) &Test-2 (star) (from M1263-III experiments). The 5h prototype run-up heights have been added for scale n_d=5 (right triangles), scale n_d=26 (left triangles), scale n_d=47 (circles) and scale n_d=84 (squared).

Figure 3.6 shows that the run-up height increases as the experiment proceeds. The run-up height seems to be correlated to the profile development. In small scale experiments, which already assumed to be ´fully´ developed for t<3h, the run-up height stays pretty constant. The run-up height in large-scale experiments increases as the experiment proceeds. The duration of the experiments is too short to reach an equilibrium state.

Shape and length of the profile seaward of the dune foot

The observed profile developments in small scale experiments and large scale experiments are quite different (see e.g. figure 3.4). The profile development in small scale experiments seems to be dominated by the slumping of the dune face due to the instability of the dune. In figure 3.7, the process is schematized.

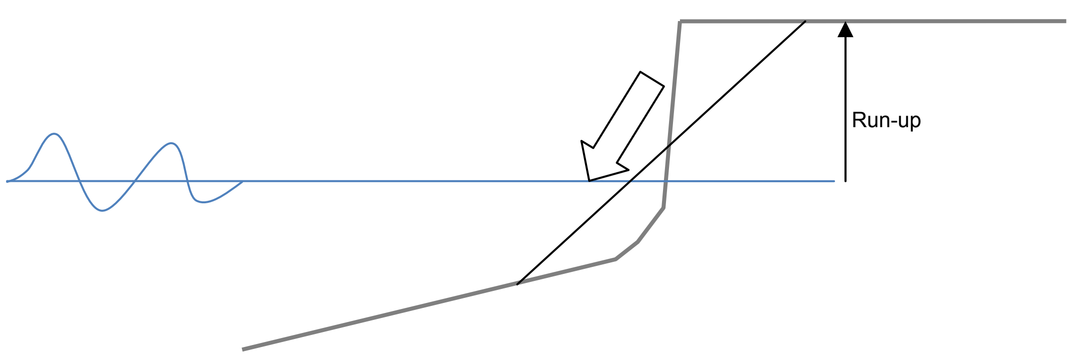


Figure 3.7: Erosion process in small-scale experiments.

When the waves hit the dune, the dune front becomes wet and instable. The run-up height determines the area that becomes wet. Because the (pre-storm) dune slope is steeper than the critical slope of wet sediment, the dune front becomes instable and starts to slump.

A similar process is observed in the large scale experiments. Different from the small scale experiment, the dune sediment that was slumped to the beach is transported further seawards due to the transport capacity of the near-shore hydrodynamics (see figure 3.8).

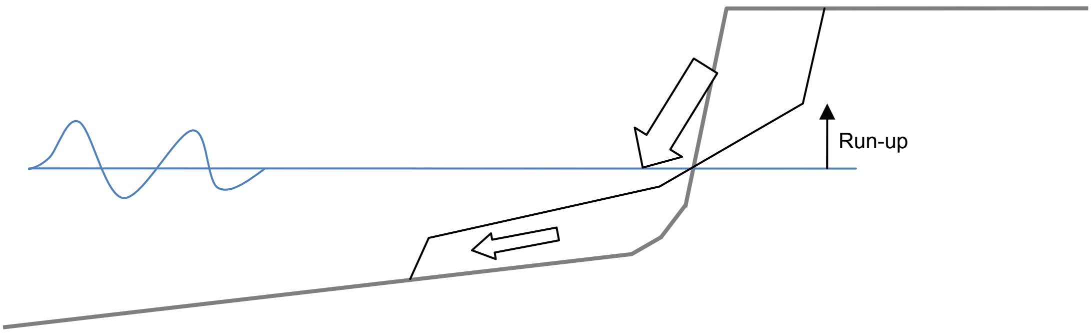


Figure 3.8: Erosion process in large-scale experiments.

It is hypothesized that the transport capacity of near-shore hydrodynamics increases, when the ratio between waves (wave height) and grains (grain size) is higher. The grains are the same for all scales. Because the wave heights at a small-scale experiments are smaller than at a large-scale experiments, the transport capacity in small-scale is smaller than in large-scale. This is also observed when comparing experiments on different scales with the same sediment property.

3.4 Comparing observations with scale relations

In section 2.5 the scaling rules of Vellinga were evaluated. The scaling rules were created to relate erosion volumes of experiments on different laboratory scales. Vellinga (1986), Hughes (1993) and Van Rijn (2010) have shown that the distortion relation by Vellinga can be used to relate laboratory profiles on different scales, if erosion processes are comparable. In this section, the scaling rules are used to compare the profiles of the different laboratory experiments. Two relations were used to test the applicability of the scaling rules for the M1263 experiments (with D_{50}=225µm).

Spatial relation: $$n_l / n_d = \left(n_d / n_{ws}^2 \right)^{0.28} \quad (3.1)$$

Temporal relation: $$n_{Tm} = n_t = \sqrt{n_d} \quad (3.2)$$

Profile evolution in time

The distortion relation assumes the morphological timescale is similar to the hydrodynamic timescale. Table 3.2 shows that for small-scale experiments a quasi-equilibrium state was reached after 3h simulation and for large scale experiments after >10h simulation. The lack of laboratory data restricts us to draw solid conclusion from these trends. For practical purposes, from now on it was assumed that the morphological and hydrodynamic timescale are similar.

Slope at the dune (-face)

The slopes at the dune (-face) were extracted from the data and shown in table 3.3. According to the distortion relation, slopes on different scale can be related by:

$$n_\phi = \frac{\Delta y}{\Delta x} = \frac{n_d}{n_l} = \frac{n_d}{n_d^{1.28} n_{ws}^{-0.56}} = n_d^{-0.28} n_{ws}^{0.56} \quad (3.3)$$

The experiments all have the same sediment property, therefore n_{ws}=1 and relation 3.3 becomes:

$$n_{\phi} = n_d^{-0.28} \tag{3.4}$$

Depth scale (n_d)	Measured ϕ_{run-up} [-] (D_{50}=225μm)	Computed ϕ_{run-up} [-]
84	0.21	0.232
47	0.19	0.197
26	0.17	0.167
5	0.11	0.105
1 (prototype)	-	*0.067*

Table 3.4: Measured and computed (with relation 3.5) run-up slope in laboratory and prototype.

When fitting all laboratory slopes with relation 3.5 a prototype slope was found of β=0.067.

$$\phi_{run-up} = \beta * n_d^{0.28} = \frac{\Delta y_r}{\Delta x_r} \tag{3.5}$$

With y_r and x_r, the run-up height and length. Table 3.4 shows that the run-up slopes can fairly well be described with the distortion relation of Vellinga.

Vertical position of the dune foot: wave run-up height

The shape of the profile, especially the part above surge level shows a systematic dependency on the scale factor. The systematic dependency above storm surge level must be due to the scale effects in the wave run-up (Vellinga, 1986). The difference could be explained by a not properly scaling of the surf similarity parameter.

The run-up heights measured in laboratory were evaluated with the general formula for wave run-up on dikes (Van der Meer and Janssen, 1994):

$$\frac{R_{u2\%}}{H_s} = 1.6\gamma_h \gamma_f \gamma_\beta \xi_{eq} \tag{3.6}$$

$R_{u2\%}$	2% run-up level above the still water level
H_s	Significant wave height
ξ_{eq}	Equivalent parameter for a slope with a berm $\xi_{eq} = \gamma_b \xi_{op}$
ξ_{op}	Breaker parameters $\xi_{op} = \tan\theta / \sqrt{2\pi H_s / \left(gT_p^2\right)}$
tan θ	Run-up slope
γ_b	Reduction factor for a berm
γ_h	Reduction factor for a shallow foreshore
γ_f	Reduction factor for slope roughness
γ_β	Reduction factor for oblique wave attack

When all reduction factors and $(2\pi)^{-0.5}$ are combined in $\gamma_{reduction}$, relation (3.6) can be rewritten to:

$$R_{u2\%} = \gamma_{reduction} T_p \sqrt{gH_s} \tan\theta \tag{3.7}$$

Battjes (1974) has shown that the wave run-up (R_v) for dikes can be described by:

$$R_v = 0.7 T_p \sqrt{gH_s} \tan\theta \tag{3.8}$$

Table 3.5 provides the run-up heights (R_{um}) measured during the experiment averaged over all experiments. The measured run-up heights in the laboratory are measured above the still water level. The computation with the Battjes (1974) relation shows for all scales an overestimation of the run-up heights. Probably, this is caused by relative shallow foreshore of beaches, described by γ_h and by the relative rough slope of sandy slopes described by γ_f. In figure 3.9, the problem is visualized.

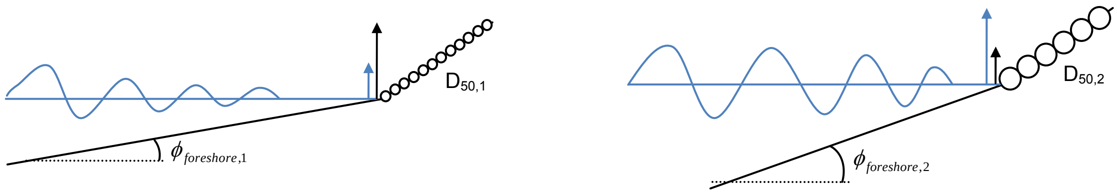


Figure 3.9: Reduction factors for wave run-up. Left: On a relative shallow foreshore the wave energy dissipates over large area. The run-up is therefore less than on a relative steep foreshore (blue arrow), because a large part of the wave energy is already lost. Right: The grain size on the slope affects the run-up height: larger grains result in more roughness and a smaller run-up height (black arrow). In small-scale experiments the relative roughness of grains is higher than in large-scale.

In coastal profiles with a relative shallow foreshore the wave energy dissipates over a relative broad area. The wave run-up is dependent on the wave energy just in front of the dune; as the wave energy in front of the dune is related to the foreshore slope, the reduction factor for a shallow foreshore is a function of the foreshore slope, so:

$$\gamma_h = \oint\left(\phi_{foreshore}\right) \quad (3.9)$$

The (prototype) foreshore slope gradient was defined as the slope between the -3 N.A.P. depth contours and the dune toe (+3 N.A.P.). Scaling of the foreshore slope can be done with relation (3.4).
The reduction factor for the slope roughness is related to the grain size on the run-up slope. At this stage, a relation for the slope roughness was not deduced, because all experiments have the same sediment property. The run-up heights were computed with a renewed run-up formula in which the foreshore reduction factor is implicitly related to the scale factor, through the model distortion (see table 3.5). The value 5.9 was gathered by calibration:

$$R_{u2\%} = 5.9\phi_{foreshore}T_p\sqrt{gH_s}\tan\phi_{run-up} \quad (3.10)$$

Scale	t_{lab} (=5$n_d^{-0.5}$) [h]	Measured run-up height R_{um} [m]	Foreshore slope $\phi_{foreshore}$ [-]	Computed run-up R_v [m]	Computed run-up $R_{u2\%}$ [m]
84	0.55	0.126*	1:13.0	0.204	0.131
47	0.73	0.165*	1:15.3	0.308	0.169
26	0.98	0.235	1:18.1	0.470	0.218
5	2.24	0.411	1:28.7	1.531	0.447
1	5	-	1:45	-	*0.906*

*Table 3.5: The measured run-up heights on laboratory scale (third column). *Extrapolated run-up heights from figure 3.6. The computed run-up heights on laboratory scale are obtained with the (basic) Battjes relation (3.8). In the last column, the scale effect of the (theoretical) foreshore slope was taken along with relation (3.10).*

The run-up heights were calculated with the new run-up formula, using the slopes from table 3.3. Note that the value 5.9 represents a calibration factor. The computed run-up heights are in nearly perfect agreement with the measured values.

The scale factor for run-up can be derived from relation (3.10) as follows:

$$n_{R_{u2\%}} = n_{\phi,\,foreshore} n_{\hat{T}} \left(n_{H_s}\right)^{0.5} \tan\theta \tag{3.11}$$

$$n_{R_{u2\%}} = n_d^{-0.28} n_d^{0.5} n_d^{0.5} \left(n_d / n_l\right) = n_d^{1.72} / n_d^{1.28} = n_d^{0.44} \tag{3.12}$$

In which $n_l = n_d^{1.28}$ (see eq. (2.33)) Equation (3.12) indicates that run-up height in laboratory experiments (scale n_d) with prototype sediment is a factor $n_d^{(1-0.44)} = n_d^{0.56}$ too large (compared to wave run-up in the field). In other words: Due to model distortion, the wave run-up scales with $n_d^{0.44}$ instead of n_d .

Shape and length of the post-storm profile seaward of the dune foot

To test the scale relations on the validity for up scaling profile shapes, laboratory profiles were converted to the prototype scale using the Vellinga relations (Eq. 3.1 and 3.2). The corresponding laboratory simulation times are listed in table 3.6.

Scale (n_d) [-]	Desired simulation time [h]	Actual simulation time [h]
1	5.0	-
5	2.2	1.0
26	1.0	0.8
47	0.7	0.6
84	0.5	0.2

Table 3.6: The desired simulation time (with relation $n_t = \sqrt{n_d}$) and the actual simulation time on various scales.

For each laboratory scale, two experiments were chosen that have comparable hydrodynamic conditions according to the Froude relation. In figure 3.10 and figure 3.11 prototype profiles are plotted.

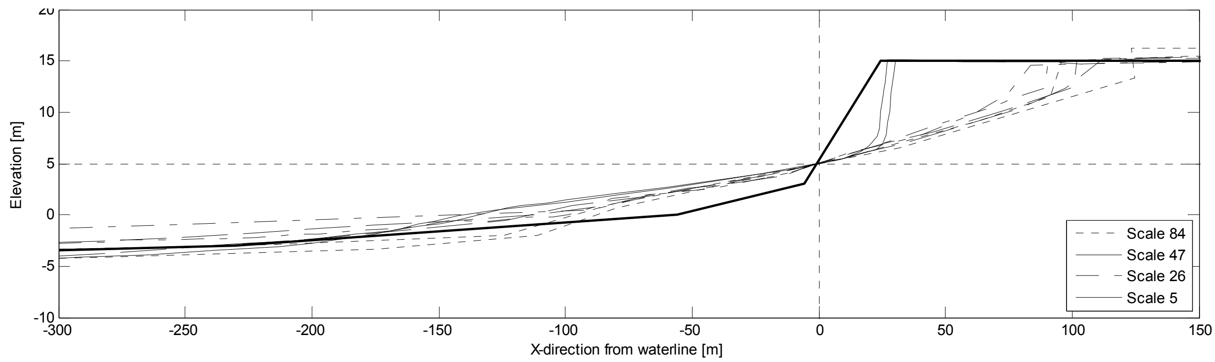


Figure 3.10: Prototype profiles after 5h simulation: testing Vellinga's scale relation. The fat line is the initial profile.

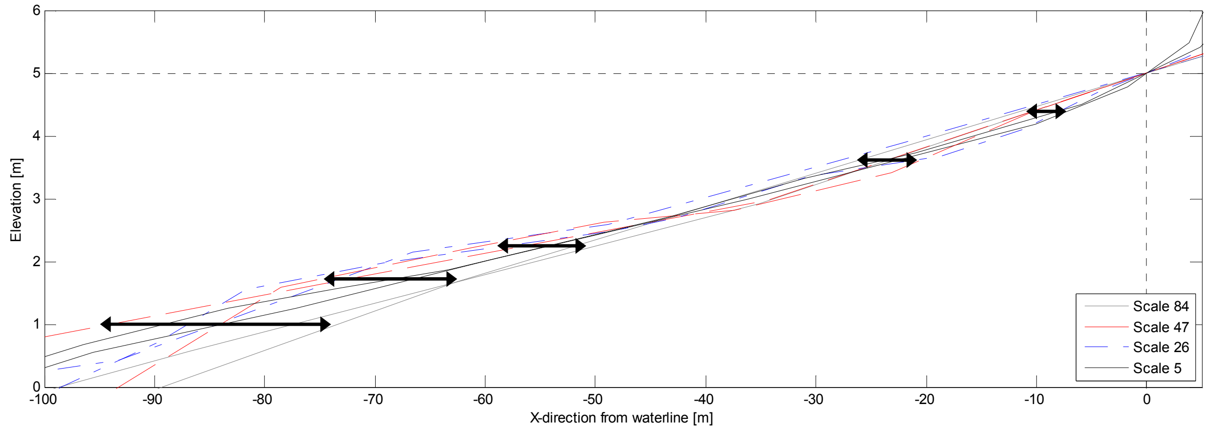


Figure 3.11: Prototype profiles after 5h simulation: Zooming post-storm profiles from figure 3.9 between depth contours MWL and SSL.

Figure 3.10 shows that the distortion relation for the scale dependency of sediment transport, introduced by Vellinga (1986), seems to work quite well from approximately +2m N.A.P. to +7m N.A.P., when comparing the horizontal variations between measurements to the horizontal development of the profile. When comparing post-storm profiles in more detail (see figure 3.11), the horizontal differences between the different laboratory scales is about 5 meter above +3m N.A.P. and below +3m up to 20m (arrows in 3.11).
Note that measurement errors in small scale experiments can also contribute to the differences on prototype scale. After all, a measurement error of 1cm in the laboratory is on prototype scale already an error of approximately 1meter.

Differences in post-storm profiles above and below SSL indicate that the distortion relation by Vellinga cannot be used to relate profiles on different laboratory scales that have the same sediment property.
The distortion relation of Vellinga is only valid when the erosion processes are similar. Figure 3.7 and 3.8 indicate that the erosion processes on small-scale and large-scale are not similar, so the distortion relation of Vellinga cannot be used.

Discussion
The profiles plotted in figures 3.10 and 3.11 do not correspond with the 5h simulation time on prototype (see table 3.6). It is therefore difficult to compare the profiles on different lab scales. A more detailed analysis of the measurements showed that the horizontal variation due to these simulation differences is not in proportion with the variation between profiles found in figure 3.11. Therefore, this effect was assumed to be negligible.

The wave run-up was found to be very important in small-scale. Due to model distortion, the scaling of the wave run-up is not in proportion to the depth. In small-scale the run-up is relatively higher than in larger scales. As large scale laboratory experiments are also a distorted model of the reference profile, it was assumed that the run-up effect in large scale is also too large. The fact that the wave run-up is very important for the dune erosion (e.g. see figure 3.10), it is hypothesized that the dune erosion in distorted models (large scale and small-scale) is not representative for the reference case.

3.5 Conclusion

The analysis of the laboratory experiments, results in a list of various scale dependent characteristics of the coastal profile. For an accurate calibration (and validation) of the dune erosion models these findings need to be considered. The differences in processes on various scales (**RQ-1**) are discussed by the variation of post-storm profiles in relation to the initial profile, the (quasi-) equilibrium condition and the run-up zone. They are found to be different for other lab scales. In the last paragraph the validity of the scaling rules is discussed (**RQ-2**). They are found to be insufficient in relating lab profiles on various scales.

Variation of post-storm profiles in relation to initial profile

The post-storm profiles have a comparable shape from -3m (prototype) below surge level until the dune foot. This is based on the fact that the horizontal variation between measured profiles is relatively small in relation to the horizontal development of the profile during the experiment. Differences above dune foot and below surge level can partly be explained by the different applied initial profiles, the hydrodynamic conditions and the experiment set-up.

Equilibrium condition

As a result of the applied hydrodynamic conditions the coastal profiles change to a new equilibrium state. The time the profile needs to adapt is strongly dependent on the laboratory scale and the applied sediment. Small-scale experiments reach an equilibrium state much earlier than large-scale experiments. This also follows from the morphological time scale in the scale relations.

Run-up zone

The run-up zone is the area of the coastal profile that is repeatedly wetted by the waves that break and subsequently run up the beach. The run-up zone is bounded by the water level and the dune foot. The run-up characteristics slope and height, show a strong scale dependency. Also, the wave run-up is not in proportion to the depth ($n_{R_{u2\%}} \neq n_d$). In scale experiments the run-up height in relation to wave height is relatively high compared to the run-up height in prototype. The renewed run-up formulation, which relates the run-up height to the peak wave period, the wave height, the beach slope and the foreshore slope, seems to perform quite well for the M1263 experiments.

Scale relations

In 1984, Vellinga introduced scaling rules to relate erosion amounts of experiments on different scales. These scale relations are currently wide applied in laboratory scaling. In section 3.4, the scale relations were used to compare profile development on different scales. They can be used to relate profiles on different laboratory scales, but are not quite accurate. The differences in erosion processes in small-scale and large-scale and the scale (read: distortion) dependency of the run-up heights are the cause for the differences in post-storm profiles.

4 Dune erosion models

4.1 Introduction

Models for dune safety assessment consist of different sub models, probabilistic models, morphological models and models to generate boundary conditions. The probabilistic model determines, by extrapolation of hydro data from the last century, the hydrological conditions like water level, wave height and wave period. The morphological model calculates with the hydrodynamics, boundary conditions and the profile characteristics, the storm impact on the *dune*. In this research, the focus is on morphological models.

The morphological dune erosion models can be characterized into 3 different model concepts, empirical (DUROS), semi-empirical (SBEACH) and process based models (DUROSTA and XBEACH), that have all its own level of detail. Empirical models give an explicit relation between dune erosion amount and important physical parameters, based on large-scale experiments (SBW-Duinen2, 2008). Within this type of models, these physical parameters are not quantified individually, but are directly linked to its consequences in relation to erosion and dune foot retreat.
In semi-empirical models, the important physical processes are, in contrast to empirical models, individually described with empirical formulas.
In process-based models, are the physical processes modelled individually. In contrast to empirical models, these (sub) models try to describe the processes itself, not its consequences. The (sub) models are developed based on detailed measurements. The process-based XBeach model is capable of modelling dune erosion in 2DH (SBWDuinen2, 2008).

In this chapter, the research question (**RQ-3**); '*How sensitive are the model results for varying boundary conditions?*' will be evaluated.
The model characteristics are expected to be important for evaluating the performance of the models (chapter 5 & 6). E.g. model limitations should tell us beforehand where and why models will probably fail in performing. In the next two sections, the model characteristics of the DUROS and XBeach model are described. In section 4.4 the model sensitivity to hydrodynamics and morphology is analyzed.

4.2 DUROS-model

4.2.1 Model description

The DUROS(+) model is currently used for the safety assessment of dunes described in the technical elaborations (TRDA) of the guidelines (VTV-K6). The DUROS model is constructed by Vellinga (1983) using the provisional model (Van de Graaff, 1977) and the results of laboratory experiments M1263 (Vellinga, 1982) with the purpose to be able to predict dune *erosion* during extreme storm events. The DUROS model was revised in 2008 by Van Gent et al., resulting in the DUROS+ version. In this research, this DUROS+ version was used (except from section 5.2.3). Figure 4.3 provides an overview of all DUROS versions.

The erosion profiles gathered in the laboratory were extrapolated to a general prototype equilibrium profile. The model determines the post surge erosion profile, using the storm surge water level (SSL), the wave height H_{0s} and the wave period T_p at a water depth of -20m NAP, the average grain size D_{50} and the pre storm coastal profile.
The model is based on a simple sediment balance that is optimised by shifting the equilibrium profile along the storm surge level, until the erosion resembles the accretion (TRDA, 2006).

The DUROS post-storm profile is based on three elements (see figure 4.1);
- (1) a landward dune slope (1:1),
- (2) a parabolic 'equilibrium' profile, and
- (3) a seaward slope (1:12.5) at the end of the equilibrium profile until the initial coastal profile.

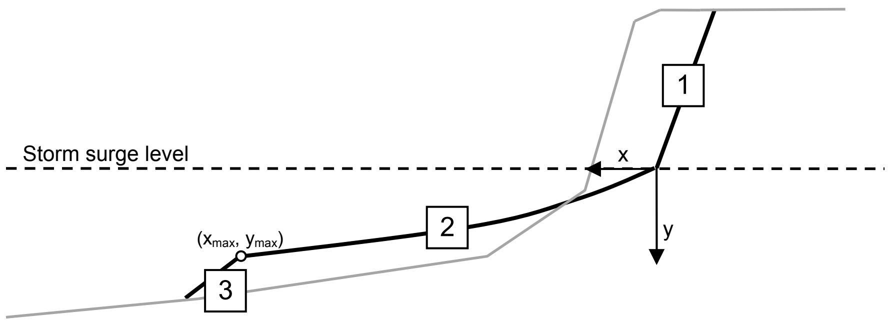


Figure 4.1: Three elements of DUROS: landward slope (1), parabolic profile (2) and seaward slope (3).

From the dune foot the equilibrium erosion profile is defined by the formula:

$$\left(\frac{7.6}{H_{0s}}\right)y = 0.4714\left[\left(\frac{7.6}{H_{0s}}\right)^{1.28}\left(\frac{12}{T_p}\right)^{0.45}\left(\frac{w_s}{0.0268}\right)^{0.56}x+18\right]^{0.5}-2.0 \tag{4.1}$$

The parabolic profile stretches from origin until the maximum offshore point, defined by the relations (4.2) and (4.3).

$$x_{\max} = 250\left(\frac{H_{0s}}{7.6}\right)^{1.28}\left(\frac{0.0268}{w_s}\right)^{0.56} \tag{4.2}$$

$$y_{\max} = \left[0.4714\left\{250\left(\frac{12}{T_p}\right)^{0.45}+18\right\}^{0.5}-2.0\right]\left(\frac{H_{0s}}{7.6}\right) \tag{4.3}$$

The length of the parabolic profile is 250m. Seawards the offshore point, the transition of the erosion profile to the initial profile has a slope of 1:12.5. The critical slope of dry sand is assumed 1:1. Therefore, a slope of 1:1 is used in onshore direction of the dune foot until the intersection with the initial profile.

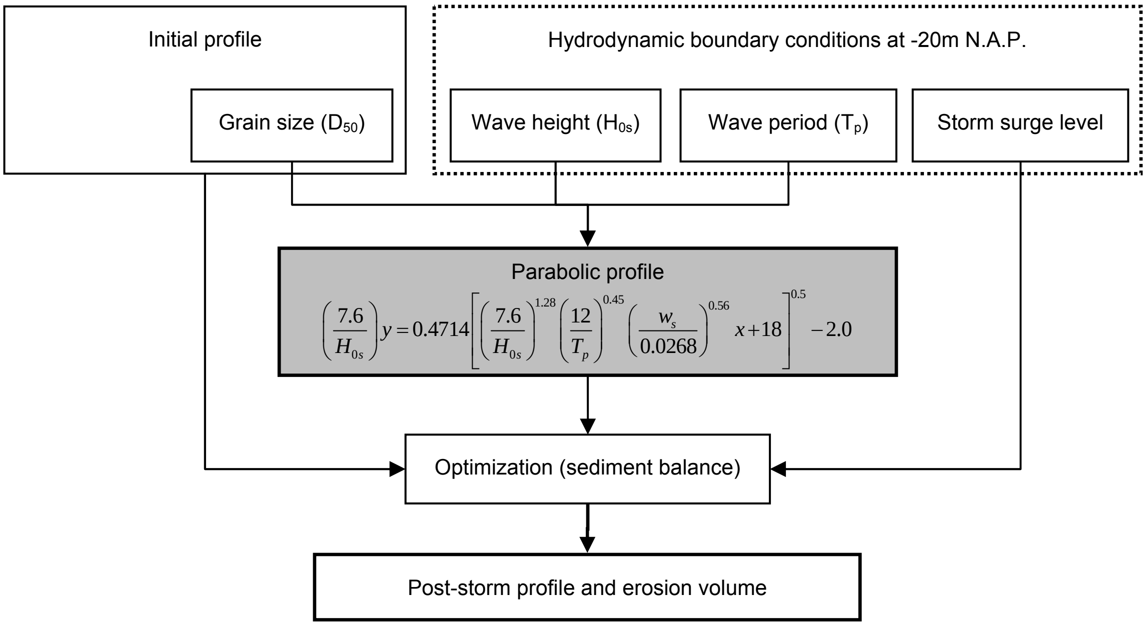


Figure 4.2: The model structure of the DUROS+ model.

In the model, the relation of the fall velocity (w_s) to the grain size D_{50} at five degrees seawater temperature is used to determine the fall velocity (WL Delft Hydraulics, 1981).

$$^{10}\log\left(\frac{1}{w_s}\right) = 0.476\left(^{10}\log D_{50}\right)^2 + 2.180\,^{10}\log D_{50} + 3.226 \qquad (4.4)$$

Processes that influence the erosion amount (others from the reference case) are implemented with sensitivity parameters of the parabolic equilibrium profile. The structure of the model in its most basic form is shown in figure 4.2.

In appendix A-1, the deduction of the current DUROS model is discussed. The deduction was originally performed by Vellinga (1986). For the aid of a better understanding of the model's assumptions and limitations, the former deduction was reproduced.

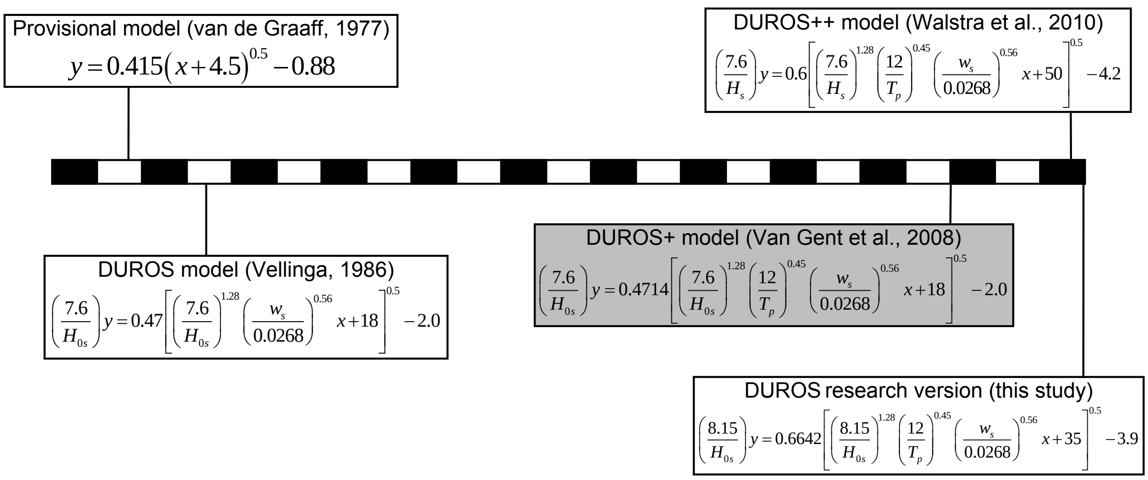


Figure 4.3: Development of the dune erosion model DUROS. Gray is the current model (as prescribed in VTV-2006).

4.2.2 Applicability and limitations

The DUROS-model is a simple equilibrium model, which predicts dune erosion by shifting the parabolic post-storm profile along the waterline until erosion and accretion relative to the initial pre-storm profile is in equilibrium. When using the model (in its most basic form), the following restrictions should be considered:

- The coastal profile should resemble the reference profile. The laboratory experiments were performed with initial profiles that equal or show small deviation from the reference profile. The DUROS model is therefore only valid for cases in which the initial coastal profiles resemble the reference profile. Recent reports, SBW-Duinen2 (2008) and Van Gent et al. (2008) showed that the model cannot be used to predict dune erosion in cases with shallow foreshore.

- The coastal curvature is minimal; the net long-shore sediment transport gradient is negligible. The model assumes a cross shore re-distribution of the sediment. If a long-shore transport gradient exists, eroded sediment can be picked by this long shore flow that results in a distortion of the sediment balance (this phenomenon is not investigated in this project).

- The model assumes an equilibrium state to be developed during a storm surge, with average storm duration of 45 hours (45h North Sea storm surge hydrograph≈5h storm with constant water level). When using the model for erosion prediction, the model overestimates and underestimates erosion amounts for resp. shorter and longer prototype storm surges.

Discussion

During the reproduction of the DUROS model, three aspects of the model were found that raised some questions: 1) the general prototype profile, 2) the calibration of the model with large-scale experiments and 3) the fall velocity formulation for sediment that is applied in the model.

The model was calibrated (by Vellinga) by changing the length of the parabolic profile (x_{max}). An optimal seaward extend of the parabolic profile is found when the predicted erosion amounts resemble the measured erosion amounts. The predicted and measured erosion amounts in the calibration process are gathered using the scaling relations of Vellinga (1986). To obtain the general prototype equilibrium profile (for DUROS) from measured laboratory profiles a different scaling factor was used by Vellinga than that of the scaling relations.
It is assumed that the processes in large-scale and prototype are similar. Therefore, the Vellinga relations can be used to create a prototype equilibrium profile. Hypothetically, when creating a prototype profile with larger scaling coefficient (0.28 in (2.39)), the prototype profile gets broader and consequently more dune volume is needed to fill-up the erosion ‘gap’ (this is the case for the general profile in DUROS). In line of this, it is assumed that the current DUROS-model overestimates dune erosion on prototype.

The parabolic profile has been cut-off at the (new) dune foot (fixed at the SSL) in landward direction and at the maximum offshore point in seaward direction. Cutting-off the parabolic profile is only fair if the run-up effect, as discussed in chapter 3, is negligible for dune erosion at prototype scale (and also in the calibration experiments). In section 3.3 it was argued that the erosion amounts in small-scale and large-scale experiments are very dependent on the wave run-up height (see also section 3.4). Hypothetically, when the (scaled) run-up heights in laboratory experiments are too large, the accompanying (scaled) erosion amounts in laboratory experiments are also too high. In line with this, it is assumed that the current DUROS-model overestimates dune erosion on prototype because the model was calibrated with too large erosion amounts on experiment scale.

The strong scale (distortion) dependency of the run-up zone and the scale dependency of the erosion processes, that was found analysing the laboratory experiments *may* also result in an unrealistic shape of the predicted profiles when verifying the DUROS-model with laboratory measurements (see chapter 5).

The erosion amount, predicted with DUROS is strongly dependent on the grain size (see figure 4.9). The grain size D_{50} is integrated in the model through the fall velocity component for seawater (equation 4.4). The fall velocity for prototype sediment size is w_s=0.0247m/s. The reference fall velocity in the model is w_s=0.0268m/s (fall velocity for fresh water). This difference leads to 27m^3/m <u>more</u> dune erosion on prototype (for the reference case). The choice for using this formulation is not wrong, but the discrepancy between the two fall velocities should be considered further on.

4.3 XBeach-model

The XBeach-model consists of different sub-models that model nearshore processes separately. Combining the different sub-models leads to sediment transport and consequently dune erosion. The XBeach-manual on the XBeach-website contains a detailed description of the model. Section 4.3.1 provides the qualitative description of the model (chapter 1 of the Roelvink et al., 2010). In section 4.3.2, the avalanche algorithm that has large influence of the actual *dune* erosion, is discussed. A mathematical model description is found in Roelvink et al. (2009).

4.3.1 Model description

XBeach is a two-dimensional process-based prediction tool, which contains the essential physics of dune erosion and overwash, avalanching, swash motions, infragravity waves and wave groups.
With regard to dune erosion, the development of a scarp and episodic slumping after undercutting is a dominant process (van Gent et al., 2008). This supplies sand to the swash and surf zone that is transported seaward by the backwash motion and by the undertow; without it the upper beach scours down and the dune erosion process slows down considerably.
Swash motions are up to a large degree a result of wave group forcing of infragravity waves (Tucker, 1954). Depending on the beach configuration and directional properties of the incident wave spectrum both leaky and trapped infragravity waves contribute to the swash spectrum (Huntley et al., 1981). Raubenheimer and Guza (1996) show that incident band swash is saturated, infragravity swash is not, therefore infragravity swash is dominant in storm conditions.

The aim of XBeach is to model processes in different regimes as described by Sallenger (2000): 1) swash regime, 2) collision regime, 3) overwash regime and 4) inundation regime. Dune erosion goes together with the swash and collision regime. The approach to model the processes in these regimes are described below:

To resolve the swash dynamics the model employs a novel 2DH description of the wave groups and accompanying infragravity waves over an arbitrary bathymetry (thus including bound, free and refractively trapped infragravity waves). The wave group forcing is derived from the time-varying wave action balance e.g. Phillips (1977) with a dissipation model for use in combination with wave groups (Roelvink, 1993a). A roller model (Svendsen, 1984, Nairn et al., 1990, Stive and de Vriend, 1994) is used to represent momentum stored in surface rollers which leads to a shoreward shift in wave forcing.
The wave-group forcing drives infragravity motions and both long shore and cross-shore currents. Wave-current interaction within the wave boundary layer results in an increased wave-averaged

bed shear stress acting on the infragravity waves and currents (e.g. Soulsby et al., 1993 and references therein). To account for the randomness of the incident waves the description by Feddersen et al. (2000) is applied which showed good skill for long shore current predictions using a constant drag coefficient (Ruessink et al., 2001).

Surf and swash zone sediment transport processes are very complex, with sediment stirring by a combination of short-wave and long-wave orbital motion, currents and breaker-induced turbulence. However, intra-wave sediment transports due to wave asymmetry and wave skewness are expected to be relatively minor compared to long-wave and mean current contributions (van Thiel de Vries et al., 2008). This allows for a relatively simple and transparent formulation according to Soulsby – Van Rijn (Soulsby, 1997) in a short-wave averaged but wave-group resolving model of surf zone processes. This formulation has been applied successfully in describing the generation of rip channels (Damgaard et al., 2002 Reniers et al., 2004a) and barrier breaching (Roelvink et al., 2003).

In the collision regime, the transport of sediment from the dry dune face to the wet swash, i.e. slumping or avalanching, is modelled with an avalanching model accounting for the fact that saturated sand moves more easily than dry sand, by introducing both a critical wet slope and dry slope. As a result slumping is predominantly triggered by a combination of infragravity swash run-up on the previously dry dune face and the (smaller) critical wet-slope (see section 4.3.2).

To this end, the code has the following functionalities (for modelling dune erosion processes):
Flow
- Depth-averaged shallow water equations including time-varying wave forcing terms; combination of sub- and supercritical flows,
- Numerical scheme in line with Stelling and Duinmeijer method, to improve long-wave run-up and backwash on the beach. The momentum-conserving form is applied, while retaining the simple first-order approach,
- Generalized Lagrangean Mean (GLM) approach to represent the depth-averaged undertow and its effect on bed shear stresses and sediment transport, cf. Reniers et al. (2004),
- Smagorinsky viscosity formulation,
- White-Colebrook roughness,
- Quasi 3D formulation,
- Automatic time step based on Courant criterion, with output at fixed or user-defined time intervals,
- Non-hydrostatic formulation.

Waves
- Time-varying wave action balance including refraction, shoaling, current refraction and wave breaking,
- Roller model, including breaker delay,
- Wave amplitude effects on wave celerity,
- Wave-current interaction,
- Roelvink (1993) wave dissipation model for use in the non-stationary wave energy balance (in other words, when the wave energy varies on the wave group timescale),
- Baldock et al. (1998) wave dissipation formulation for stationary wave energy balance.

Sediment transport and bed updating
- Depth-averaged advection-diffusion equation to solve suspended transport,
- Bed updating algorithm including possibility of avalanching,

- Soulsby – Van Rijn transport formulations, cf Reniers et al. (2004),
- Intra-wave sediment transport,
- Avalanching mechanism, with separate criteria for critical slope at wet or dry points.

The XBeach-model was tested and calibrated with large-scale Deltaflume experiments performed in 2006 (see Van Thiel de Vries, 2009 for more details). The parameter settings in the model are chosen that the erosion processes, profile development and dune erosion in these experiments can be reproduced by the model. These model settings are assumed to be default in this research (see appendix A-2).

4.3.2 Dune face erosion in XBeach

The dune face erosion in a coastal profile is caused by the repeatedly hitting of waves against the dune. The interaction of the dune face and the swash zone, causing that episodically sand is released from the dune by slumping is complex and the processes involved are far from understood. Several attempts have been made to model the dune erosion process. The linear relation between wave impact and eroded dune volume proposed by Fisher et al. (1986) has been examined in detailed with the Delta-flume experiments and performs very well (Van Thiel de Vries, 2009). In the XBeach-model, the dune face erosion is modelled with an avalanche algorithm. This algorithm is described below.

Avalanche algorithm

In XBeach, the dune erosion rate is determined by the capacity of the near dune hydrodynamics to transport sediment in offshore direction but is also dependent on the sediment supply from the dune. The sediment supply from the dune face is simulated with an avalanche algorithm (see figure 4.4). The avalanche algorithm considers a critical wet slope ($\phi_{cr,wet}$) below the water surface and a critical dry slope ($\phi_{cr,dry}$) for the dry area with dunes and at the beach. The transition of the critical wet slope to the critical dry slope takes place at a user specified water depth (h_{switch}). The maximum erosion rate of the dune face in the avalanche algorithm (dz_{max}) is also specified (Van Thiel de Vries, 2009).

In the model long waves contribute to the avalanching since they inundate the upper beach and dune face during run up. When stable dry points become wet they might become instable and avalanche.

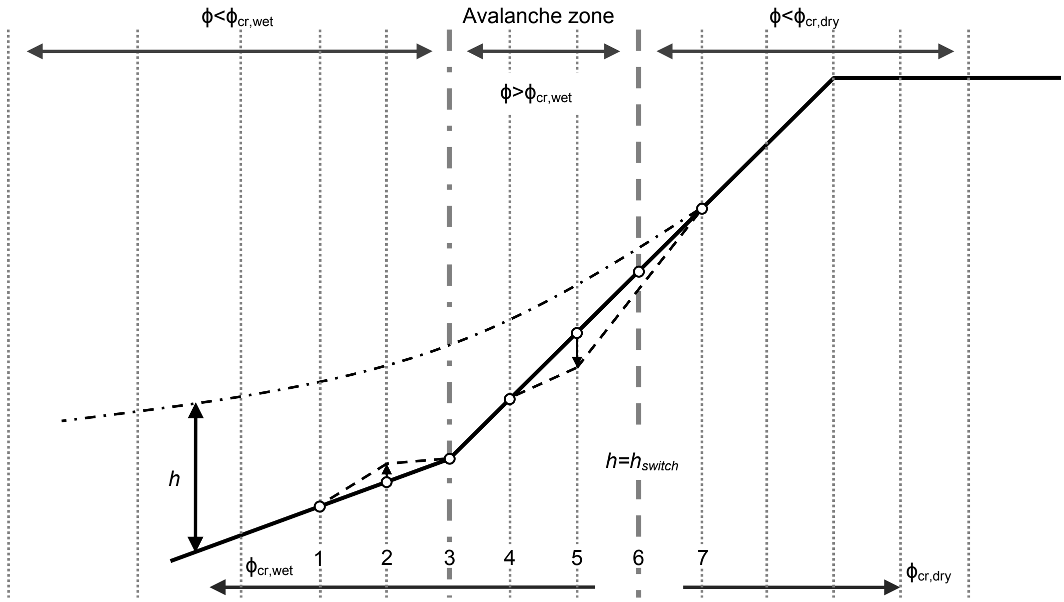


Figure 4.4: The avalanching algorithm in the XBeach model. The bed is indicated by the black solid line. The water surface is indicated by the black dashed-dotted line and the computational bed level points by the vertical gray dotted, dashed and dashed-dotted lines. The bed level points are instable between the fat gray dashed-dotted line and the fat gray dashed line that show the transitions towards a steeper bed slope ($\phi>\phi_{cr,wet}$) and to dry points ($h>h_{switch}$) respectively (Van Thiel de Vries, 2009).

Note: The transitions towards a steeper bed slope and to dry points are not fixed at one specific bed level point, but are dependent on resp. the sediment transport capacity of nearshore hydrodynamics and the (user specified) h_{switch}.

$\phi_{cr,wet}$	Critical wet slope for avalanching (wetslp)	[-]
$\phi_{cr,dry}$	Critical dry slope for avalanching (dryslp)	[-]
dz_{max}	Maximum avalanche rate	[m^3 $s^{-1}m^{-1}$]
h_{switch}	Water depth at wet-slope/dry-slope interface	[m]

When the critical slope between two adjacent grid cells is exceeded, sediment is exchanged between these cells to the amount needed to bring the slope back to the critical slope. This exchange rate is limited by a (user specified) maximum avalanching transport rate (dz_{max}).
In the XBeach model simulations, the avalanching mechanism is typically triggered when a high infragravity wave reaches the dune front and partly inundates it. The critical underwater slope is suddenly exceeded and the two grid cells at the dune foot are adjusted during the first time step when this happens. In subsequent time steps a chain reaction may take place both in landward points (≥7), where now the critical dry slope may be exceeded because of the lowering of the last wet point (6), and in seaward points (3-5), where now the critical wet slope may be exceeded. As a result, sediment is brought from the dry dune into the wet profile, where it is transported further seaward by undertow and infragravity backwash (Roelvink et al., 2010).

4.3.3 Limitations

The amount of dune erosion is dependent on the transport capacity of nearshore hydrodynamics and the supply of sediment from the dune. The earlier described avalanche algorithm determines the amount of sediment that was ‘released’ from the dune. A sensitivity analysis of the avalanche parameters was performed (see figure 4.5). The (default) parameter magnitudes were obtained by model calibration at Deltaflume scale n_d=6. The parameters (indicated with A) were expected to depend on the spatial scale, the model was applied to.

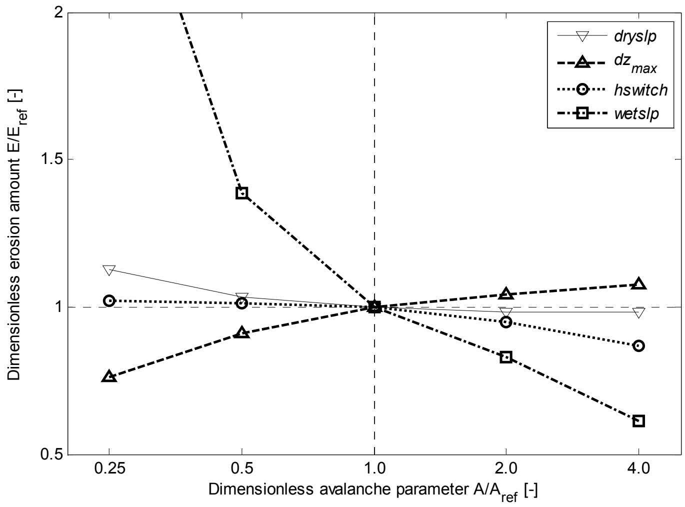


Figure 4.5: Sensitivity of avalanche parameters; dryslp, dzmax, hswitch and wetslp.

Figure 4.5 shows that the erosion amount is very sensitive to the avalanche parameters *wetslp* and *dzmax* and less sensitive to parameters *dryslp* and *hswitch*. For model application choosing the correct magnitude of these parameters is essential. Incorrect parameter configuration leads to unrealistic model simulations (e.g. see section 5.3.2).

4.4 Model sensitivity DUROS and XBeach

In this section the sensitivity of the DUROS+- and the XBeach-model to changing hydrodynamic and morphodynamic conditions is analyzed. The purpose of this analysis is to investigate the sensitivity of the models in a reference case to deviant boundary conditions and to verify to what extent the models give realistic results. The observations during the sensitivity analysis were used to draw some conclusions concerning the applicability of the models.

4.4.1 Hydrodynamics

The chosen hydrodynamic parameters are based on the boundary conditions prescribed in the Dutch law for safety assessment. The applied range of parameters covers the range, which can be found in the HR2006 (*Hydraulische randvoorwaardenboek*). In the sensitivity analysis only one parameter is varied at the time. The others were kept constant and in conformity with the reference conditions (see table 4.1).

Parameter	Prototype conditions
Offshore significant wave height	7.6m (PM-spectrum)
Offshore peak wave period	12s
Offshore water depth	20m
Maximum storm surge level	+5 N.A.P.
Storm duration (SSL)	45h North Sea hydrograph (5h max. SSL)
Median sediment diameter	225µm
Median fall velocity (for seawater)	0.0248m/s
Water temperature	5°C
Cross-shore profile	Dune height at +15 N.A.P.

	Dune face with slope of 1:3 down to +3 N.A.P. Slope of 1:20 between +3m and 0m N.A.P. Slope of 1:70 between 0m and -3m N.A.P. Slope of 1:180 between -3m and -20m N.A.P.

Table 4.1: Characteristics of Reference Case.

In the next paragraphs, the sensitivity to changing hydrodynamic conditions was qualitatively analyzed by comparing the predicted profiles (elevation w.r.t. N.A.P.) for the minimum and maximum value of the parameters, the dune erosion above storm surge level and the dune retreat at +12m N.A.P. The profile (reference case) that was used is characterized by [0, -20; 3060, -3; 3270, 0; 3330, 3; 3366, 15; 3530, 15].

Parameter	DUROS parameter	XBeach parameter	Reference value	Range
Storm surge level (SSL)	WL_t	zs0	5m	3-8
Wave height (H_s)	Hsig_t	Hm0 [instat=4 (PM)]	7.6m	6-12
Wave period (T_p)	Tp_t	f_p $\left(1/T_p \right)$	12s	10-22

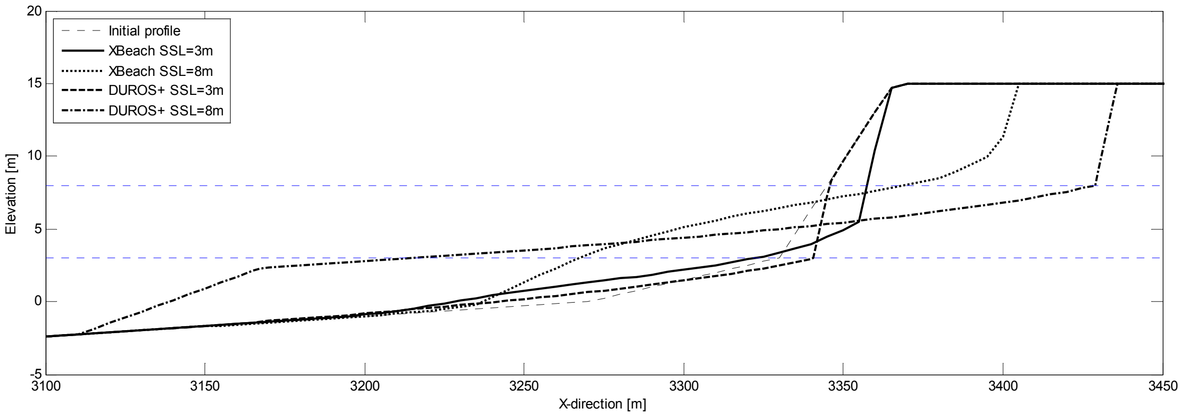
Table 4.2: Hydrodynamic conditions for testing the model sensitivity.

Compared to the boundary conditions prescribed in the HR-2006, the reference conditions are rather mild. For the northern Dutch coast the normative storm surge level is 5-5.5m, the wave height 9-11m and the wave period 16-17s. For the southern Dutch coast, this is 5.5-6m (SSL), 8-10m (H_s) and 12-16s (T_p).
The DUROS-model was applied in its most basic form, i.e. additional volumes that are prescribed in Dutch legislation were not taken along. The XBeach model was applied with an adjusted avalanche parameter; the maximum avalanche speed (in line with Van Thiel de Vries, 2009). The avalanche speed scales according to:

$$n_{dz\max} = n_d^{1.5} \tag{4.5}$$

(See section 5.3.3). Relation (4.5) results in a maximum avalanche speed of *dzmax*=0.0441m^{2}s^{-1} for prototype scale (Van Thiel de Vries, 2009). Other model settings were default (see appendix A-2).

Storm surge level



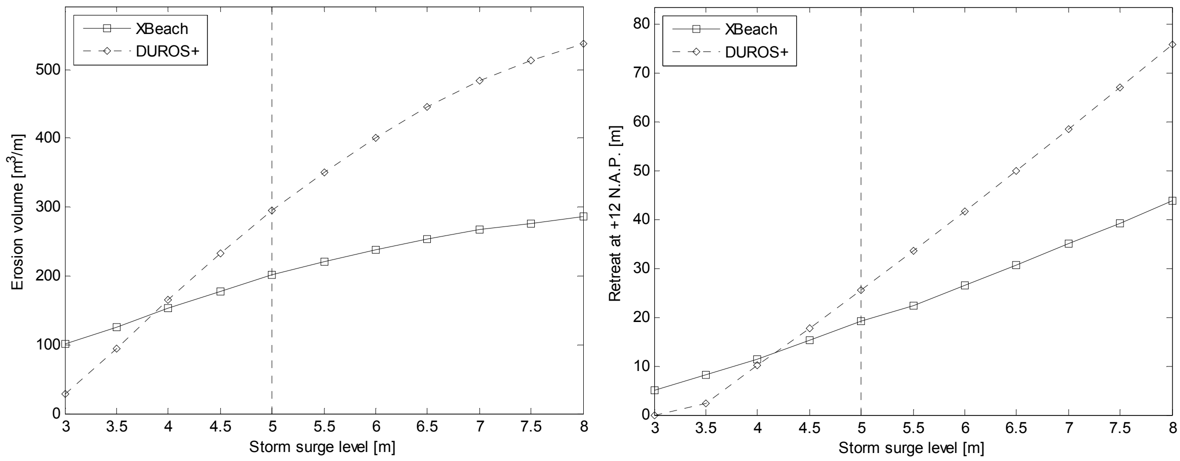
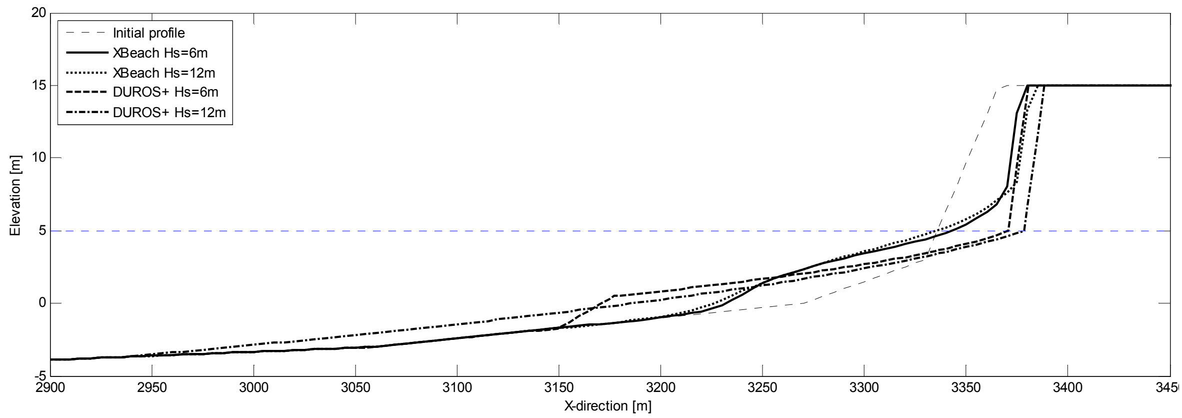


Figure 4.6: DUROS- and XBeach-model sensitivity with varying storm surge level. Upper panel: The predicted profile developments for the lowest surge level (3m) and the highest surge level (8m). Lower left panel: The erosion volume above storm surge level. Lower right panel: The dune retreat at +12 m N.A.P. The vertical dotted line indicates the reference value of the storm surge level.

In the reference case, the predicted erosion volume by the DUROS-model is approximately 40% higher than the erosion volume predicted with XBeach-model. When changing the storm surge level, the predicted erosion amount and the dune retreat change faster for the DUROS-model than for the XBeach-model, therefore the DUROS-model is much more sensitive for other surge levels than XBeach.
The predicted profile slopes for the highest and lowest storm surge level are the same for the DUROS-model. The XBeach-model predicts a steeper slope for the case with the highest storm surge level. When the storm surge level is below +4m N.A.P., the erosion amount and the dune retreat predicted with DUROS drop below the erosion amount and dune retreat predicted with XBeach.

Wave height



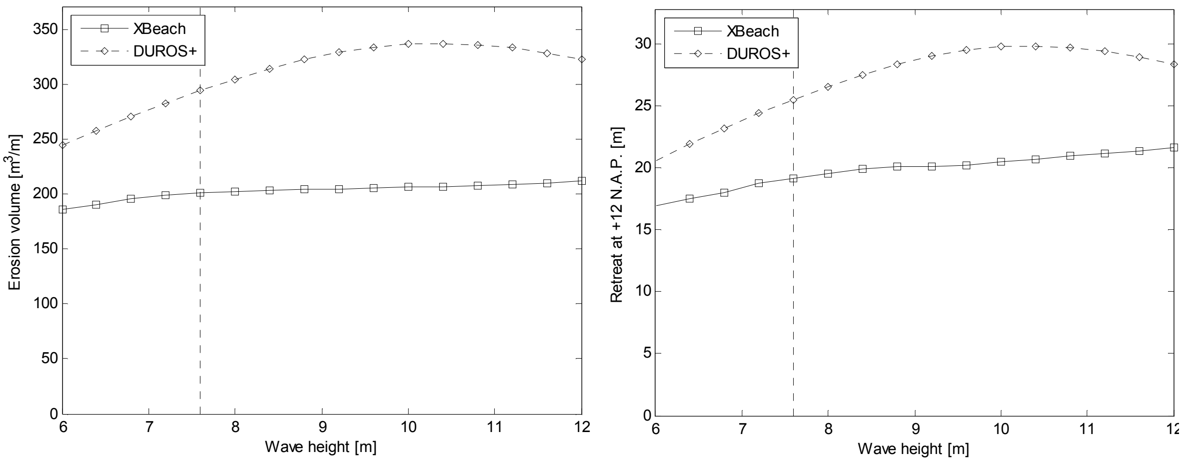


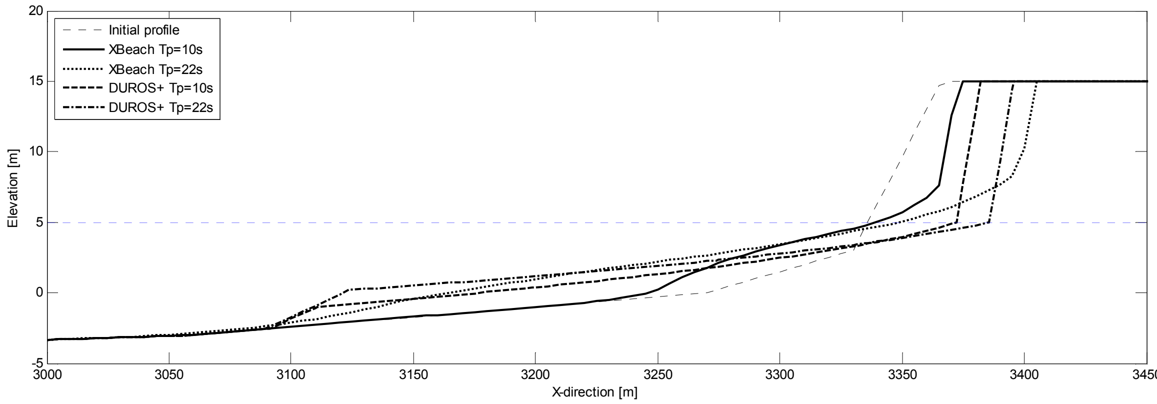
Figure 4.7: DUROS- and XBeach-model sensitivity with varying wave height. Upper panel: The predicted profile developments for the lowest wave height (6m) and the highest wave height (12m). Lower left panel: The erosion volume above storm surge level. Lower right panel: The dune retreat at +12m N.A.P. The vertical dotted line indicates the reference value of the wave height.

The XBeach-model shows to be linear dependent on the wave height for both erosion amount and dune retreat. The seaward extending is slightly larger for higher wave heights. Also, the dune foot is slightly higher for larger wave heights.

The wave height has a big influence on the seaward extend of the predicted profiles with the DUROS-model. The DUROS-model results also show a linear dependency on the wave height until a wave height of approximately 9m. Both the erosion amount and dune retreat reach a maximum for a wave height of 10.5m. After that, the erosion amount and dune retreat decrease with a larger wave height.

Assuming the wave height during a storm surge is related to the wave energy at the coast and the wave energy at the coast is related to the sediment transport at the coast, than the sediment transport increases with increasing wave height. In case of DUROS, the coastal profile becomes broader and steeper with higher wave heights (according to relation (4.1)). At a certain point the (predicted) coastal profile becomes steeper than the initial profile. In this case, the landward shift and consequently erosion amount and dune retreat decreases. Because the predicted erosion amount and dune retreat hardly increase for wave heights over approx. 10m, it was hypothesised that the DUROS-model performs insufficient for wave heights above approximately 9m for the reference case.

Wave period



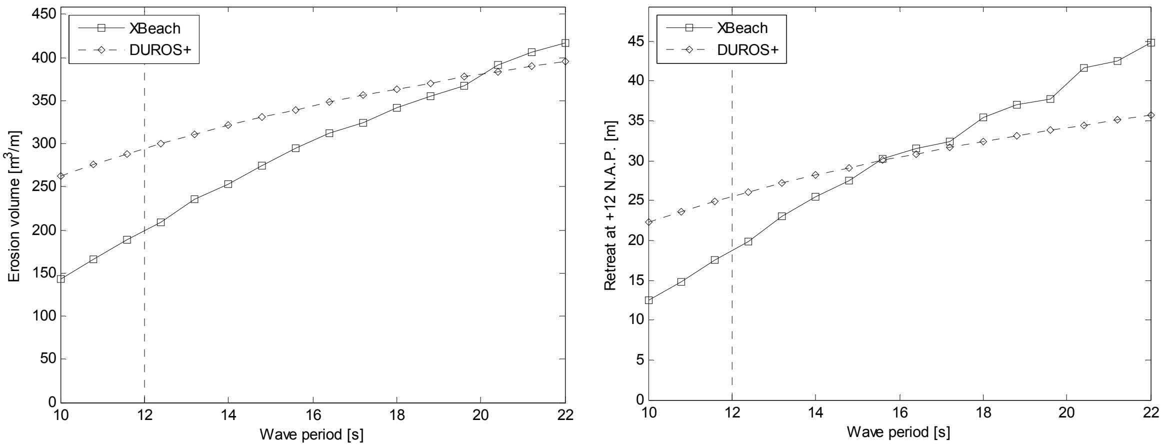


Figure 4.8: DUROS- and XBeach-model sensitivity with varying wave period. Upper panel: The predicted profile developments for the shortest wave period (10s) and the longest wave period (22s). Lower left panel: The erosion volume above storm surge level. Lower right panel: The dune retreat at +12m N.A.P. The vertical dotted line indicates the reference value of the wave period.

The DUROS-model shows an almost linear relation between the wave period and erosion amount and dune retreat. The seaward extend for the shortest wave period is almost the same as in case of the longest wave period. The wave period affects the slope of the profile. A gentle slope goes with a longer wave period; a gentler slope leads to more accretion and more erosion.
The XBeach model shows unlike DUROS a high dependency on the wave period. Both seaward extend and the height of the dune foot increase with longer wave periods. For wave periods longer than 20s, the erosion amount predicted with XBeach exceeds the erosion amount predicted with DUROS. The dune retreat predicted with XBeach exceeds the retreat predicted with DUROS for wave periods longer than approximately 16s.

4.4.2 Morphodynamics

The chosen morphodynamical parameters are based on the boundary conditions prescribed in the Dutch law for safety assessment. The applied range for the dune sediment covers the range that can be found in the *Hydraulische randvoorwaarden* (HR2006). An analysis of the Dutch cross-shore profiles (Jarkus-transects) is performed to set a range for the other parameters, dune height, dune slope and horizontal stretch of the initial profile. In the sensitivity analysis only one parameter is varied at the time. The others were kept constant and in conformity with the reference conditions.

Parameter	DUROS parameter	XBeach parameter	Reference	Range
Dune sediment	D_{50}	D_{50}, D_{90}(=1.5D_{50})	250µm	150-350
Dune height	*zInitial*	*“referenceprofile.dep”*	*15.0m*	*10-20*
Dune slope	*zInitial*	*“referenceprofile.dep”*	*1:2.5*	*1:10-1:1*
Horizontal expanse of initial profile	xInitial	“dx” (regular grid)	1	0.5-2

Table 4.3: Morphological conditions for testing the model sensitivity.

In the next paragraphs the sensitivity to changing morphodynamic conditions is qualitatively analyzed by using the predicted profiles for the minimum and maximum value of the parameter, the dune erosion above storm surge level and the dune retreat at +12m N.A.P. The results for the parameters dune height and dune slope can be found in appendix A-9. In case of changing dune height DUROS seems more sensitive than XBeach: Erosion amounts vary between 230-350m^3/m for DUROS and between 200 and 240m^3/m for XBeach. In case of changing dune slope DUROS also seems more sensitive than XBeach: Erosion amounts vary between 130-350m^3/m for DUROS and between 130 and 260m^3/m for XBeach.

Dune sediment

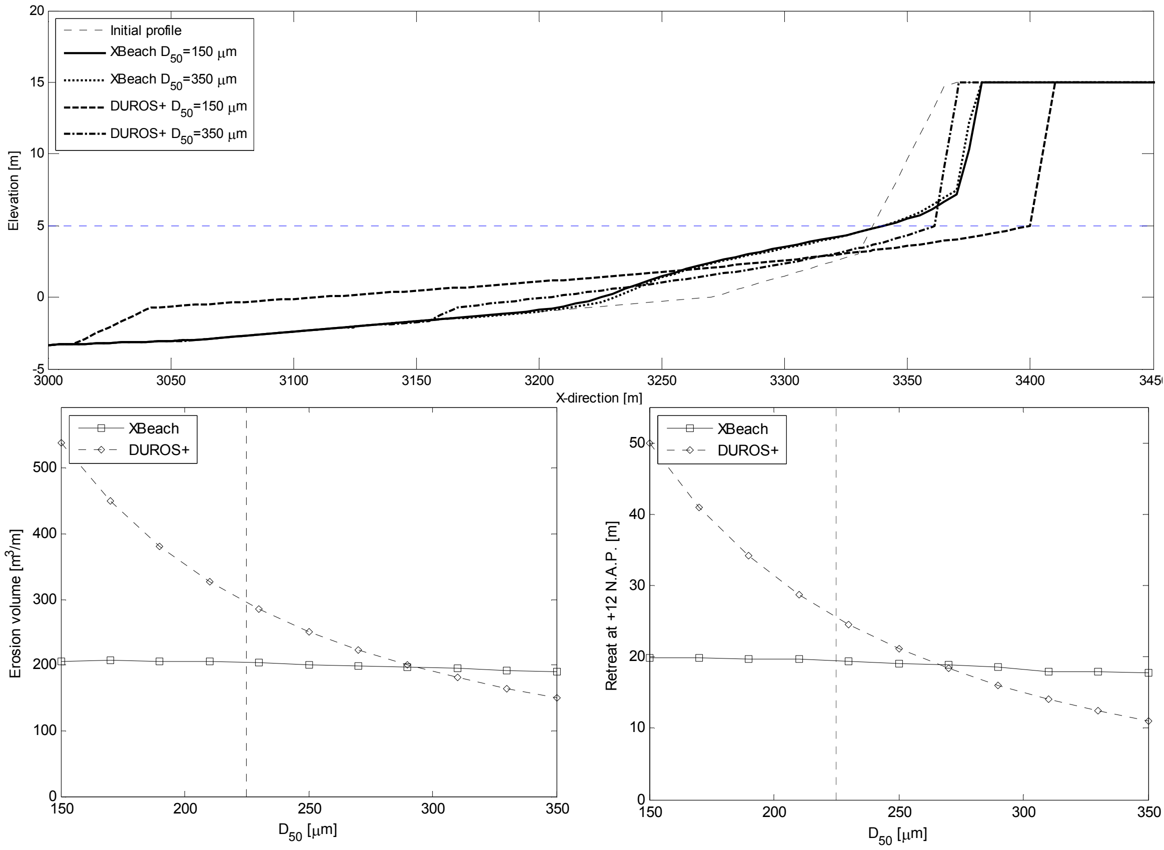


Figure 4.9: DUROS- and XBeach-model sensitivity with varying sediment size. Upper panel: The predicted profile developments for the smallest grain size (150μm) and the largest grain size (350μm). Lower left panel: The erosion volume above storm surge level. Lower right panel: The dune retreat at +12m N.A.P. The vertical dotted lines indicate the reference value of the sediment size.

The DUROS-model seems to be strongly dependent on the dune sediment size. The erosion amount for the smallest sediment size is almost two times the reference erosion amount. The seaward extend is almost two times broader for the smallest sediment size. Also the slope of the profile is gentler for smaller sediment sizes.
The XBeach-model shows minimal dependency on the sediment size. The predicted profiles for the smallest and largest sediment size are almost the same and therefore both the erosion amount and dune retreat are quite similar (+2% till -4%). The large difference between the DUROS-model and XBeach-model can be explained by:

- 1). the sensitivity in the DUROS-model that is implicitly related to the distortion relation (2.32), is too high, or

- 2). the sensitivity in the XBeach-model is too low, by:
    - o A). the sensitivity of the supply of sediment from the dune is too low (avalanching), and/or,
    - o B). the sensitivity of the demand of sediment of nearshore hydrodynamics is too low (transport formulations).

Horizontal expanse of the initial profile

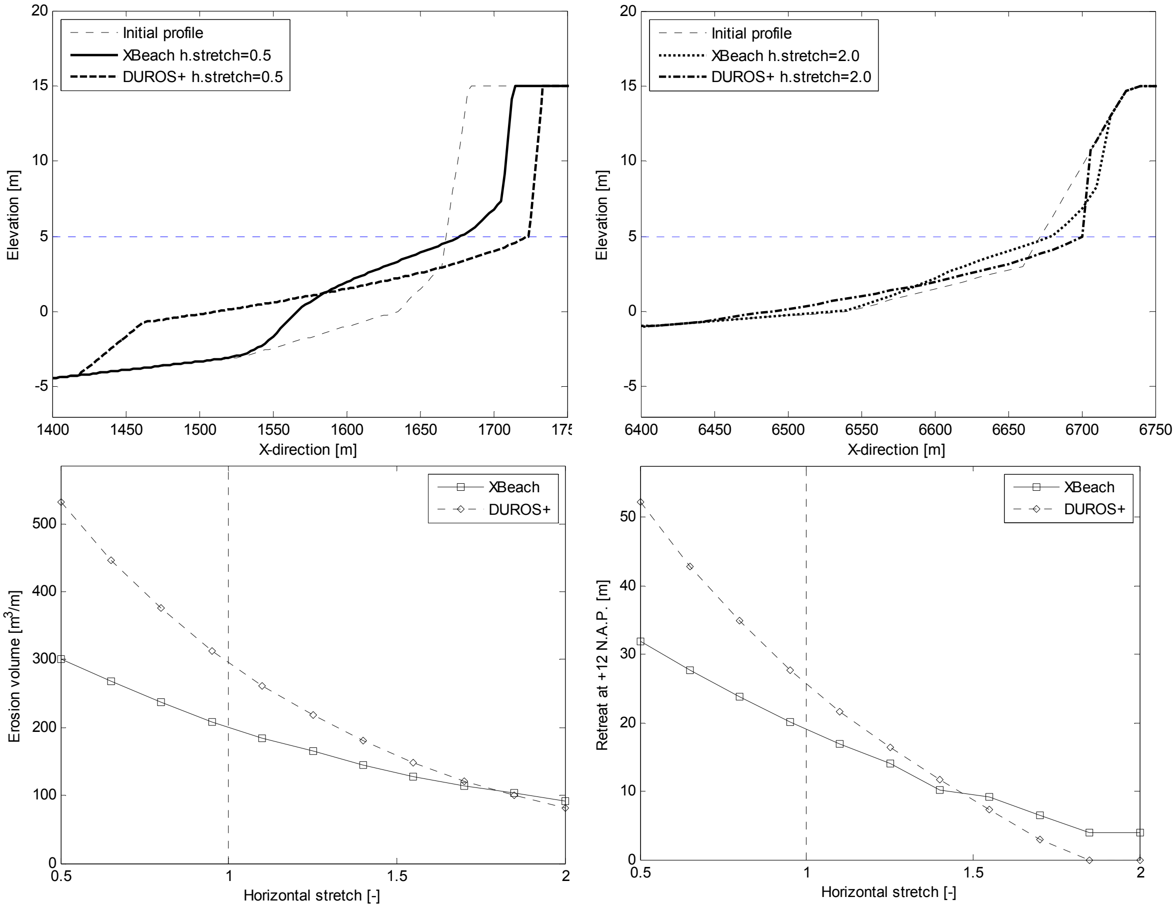


Figure 4.10: DUROS- and XBeach-model sensitivity with varying horizontal stretch. Upper left panel: The predicted profile development for the lowest horizontal stretch (0.5). Upper right panel: The profile development for the highest horizontal stretch (2.0). Lower left panel: The erosion volume above storm surge level. Lower right panel: The dune retreat at +12m N.A.P. The vertical dotted line indicates no horizontal stretch.

The DUROS-model contains a general equilibrium profile that is not dependent on the expanse of the initial coastal profile (see figure 4.11). The expanse determines the shape (i.e. the overall slope) of the initial profile. When the expansion is increased, the predicted erosion amount and dune retreat decreases. In cases with very shallow foreshore, the DUROS-model hardly predicts any dune erosion and dune retreat.

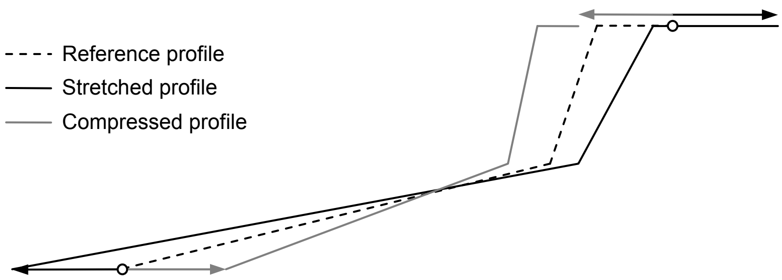


Figure 4.11: Expanse of the initial coastal profile.

The XBeach-model shows less dependency on the expanse of the coastal profile than the DUROS-model. The seaward extend of the predicted profiles are the same for different shapes of initial profiles. The erosion amount and the dune retreat decrease with higher horizontal expansion. In cases with a horizontal stretch of approximately 1.8, the predicted erosion amount with DUROS drops below the predicted erosion amount with XBeach.

4.4.3 Conclusion

The DUROS-model is an empirical model that is constructed with the results of laboratory experiments at four different scales; depth scale n_d=84, n_d=47, n_d=26 and n_d=5. The model's purpose is to compute prototype erosion amounts during extreme storm surges. The erosion amount is obtained by fitting a parabolic post-storm profile over an initial coastal profile. The shape of the parabolic profile is dependent on hydrodynamic parameters surge level (SSL), wave period (T_p) and wave height (H_s) and morphodynamic parameter sediment size (D_{50}).
When using the DUROS-model, the next model restrictions should be considered: the coastal profile should resemble the reference profile. The shoreline curvature is minimal and/or the net long-shore sediment transport is negligible (during the storm surge). A storm surge can be approximated by a 5 hour surge with constant maximum surge level.
The DUROS-model contains a parabolic prototype profile that is constructed with the results of laboratory experiments and a scaling relation. The applied scale relation, which is used by Vellinga (1986) to construct the parabolic profile, deviates from the earlier deduced scaling relation. This discrepancy possibly leads to deviant prototype profiles and therefore to deviant prototype erosion amounts. The run-up effect observed in chapter 3 was hypothesised to be very important for the dune erosion amount. This run-up effect is not included in the current DUROS-model. When verifying the DUROS-model with the laboratory experiments, the predicted profiles may show unrealistic shape in the area above surge level.

The process-based XBeach-model computes nearshore bed evolution by combining nearshore hydrodynamics with sediment transport. The dune face erosion is predicted with an avalanche algorithm that is also triggered by the near shore hydrodynamics. The avalanche algorithm is a sensitive component of the XBeach-model for the amount of predicted dune erosion.
The avalanche concept assumes wet and dry bed level points. When dry points become wet by inundation, the critical slope at those points decreases, hence they may become instable. This instability leads to avalanching. The avalanche rate is limited by the user specified maximum avalanche rate (dzmax).

Parameter	DUROS	XBeach	DUROS vs. XBeach
Surge level	++	+	>
Wave height	+	+	=
Wave period	+	++	<
Sediment size	++	+/-	>
Horizontal stretch	--	-	>

Table 4.4: Model sensitivity. Model predictions are positive (+) or negative (-) related to the parameters. In case that model A is strongly dependent on a parameter (++) and model B not or less, model A has a higher dependency than model B (A>B). In case that model A & model B are similar related to a parameter, their dependency is similar (=).

When comparing the DUROS-model and the XBeach-model for sensitivity to hydrodynamic and morphodynamic parameters, the models show some similarities but particularly differences. The DUROS-model is found to be very sensitive to the storm surge level, the sediment size and the horizontal stretch of the initial profile. On the other hand, XBeach is relatively sensitive to the wave period. For wave periods longer than 14s, the predicted erosion amount exceeds the predicted erosion amount with DUROS. When the wave height exceeds a height of approximately 10m, the DUROS-model seems to perform insufficient. The sensitivity to dune height and dune slope is the same for both models.

5 Model performance on laboratory scale

5.1 Introduction

In this chapter the model performance of both DUROS-model and XBeach-model is tested by applying them on available laboratory experiments from the M1263 project. The models differ in the level of detail to simulate the actual dune erosion. The XBeach-model consists of different sub-models that model near shore processes separately. Combining the different sub-models leads to sediment transport and consequently dune erosion. The empirical DUROS-model, on the other hand, is rather simple. It assumes one post-storm prototype equilibrium profile that is a function of the hydrodynamic boundary conditions. Computations in the DUROS-model are restricted to the optimization of the erosion/accretion balance.

For the aid of explaining the discrepancy between XBeach predictions and DUROS predictions on prototype scale, the models were tested on several laboratory experiments. It was assumed, that when models perform similarly at different laboratory scales (lines in the figure 5.1), the models will perform similar on prototype scale (dotted line). The research question; '*To what extent are the models capable of simulating dune erosion on various lab scales and what model settings have to be changed to improve the performance?'* (**RQ-4**) will be evaluated.
The DUROS-model, which is originally constructed to perform only on prototype scale, is compared to the laboratory experiments it was constructed from, using the scale relations of Vellinga. The process-based XBeach-model, which can be applied at every scale, is applied to the original laboratory experiments.

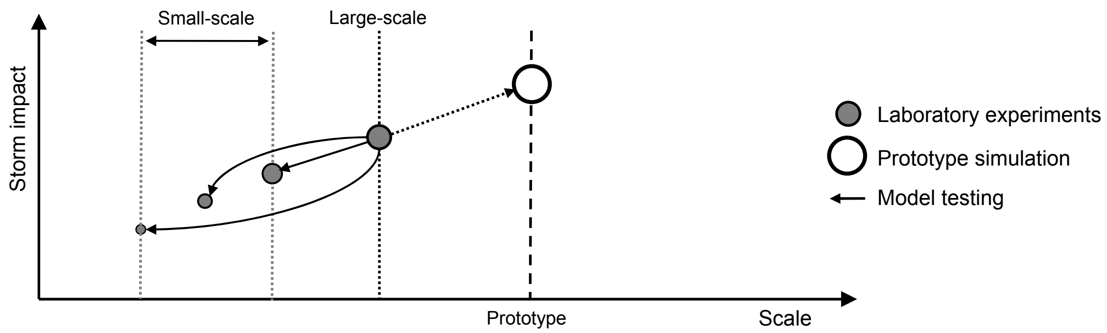


Figure 5.1: Storm impact on various scales: applying the DUROS and XBeach-model to laboratory experiments on various scales (gray circles).

In section 5.2, the current DUROS-model is compared with the laboratory experiments M1263. In section 5.3, the XBeach-model is compared with the laboratory experiments. After evaluating the model performance, some XBeach-model parameters are adjusted depending on the scale of the experiment. In the section an overview of input parameters is provided that need to be scaled to obtain reasonable model performance on different lab scales. Depending on the parameter this scaling may be different.

5.2 Comparison of DUROS with laboratory tests

5.2.1 Approach

In this section the model performance of the DUROS-model is tested. The model was compared to the laboratory experiments it was initially constructed from.

In section 4.2.2 the applicability and limitations of the model were discussed. It was argued that the model can only be applied to experiments with comparable erosion processes and run-up heights. In section 3.3 it was found that the processes in small-scale and large-scale are quite different, where the processes in large-scale are most representative for prototype processes. In line with this, it is expected that the model performs relatively better at large-scale than at small-scale experiments. In section 5.2.2 the performance of the DUROS+ model is evaluated with all laboratory experiments available from the M1263 project.

5.2.2 Verification of DUROS model

Experiments
In this section the performance of the DUROS-model is verified with the laboratory experiments on four different scales (see appendix A-1). For the purpose of a good prototype representation, laboratory experiments are chosen that have comparable prototype simulation time. The corresponding laboratory simulation times are calculated with the Froude relation:

$$n_{Tm} = n_t = \sqrt{n_d} \qquad (5.1)$$

The laboratory simulation times are shown in table 5.1. The table also gives an overview of the chosen experiments from M1263 (I-III) (see appendix A-3 for all experiments).

Depth scale (n_d)	Simulation time [h]	Experiment [#]	Length scale (n_l)	References
5	2.24	Test-1 (3h)	7.85	WL|Delft Hydraulics (1984)
26	0.98	Test-121 (1h)	64.74	WL|Delft Hydraulics (1981)
47	0.73	Test-101 (1h)	138.13	WL|Delft Hydraulics (1976)
84	0.55	Test-111 (1h)	290.45	WL|Delft Hydraulics (1981)

Table 5.1: Chosen experiments for detailed DUROS+ verification.

Model set-up
In order to evaluate the performance of the DUROS-model with the chosen laboratory experiments, the lab profiles have to be converted to a prototype profile. This is performed by multiplying lab profiles with n_d and n_l, gathered with the distortion relation (2.32) (Vellinga, 1986). The prototype initial profile is the input profile for the DUROS-model. After simulation, the predicted post-storm profile is converted back to lab profiles. Afterwards, the predicted and measured lab profiles are compared. This process is schematized in figure 5.2.

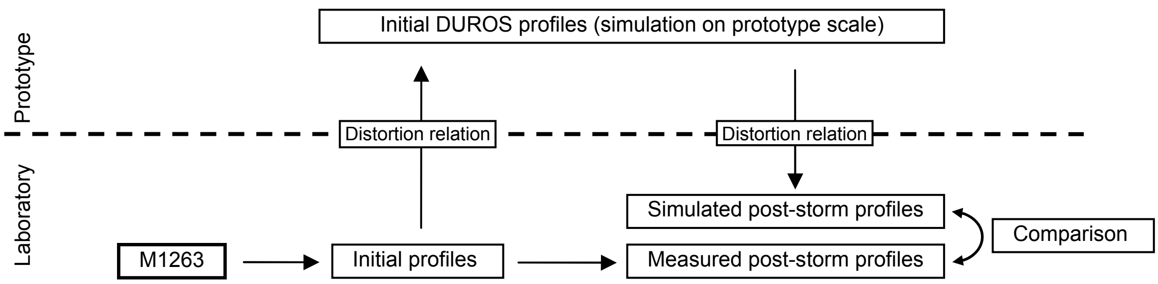


Figure 5.2: Scheme for comparing the DUROS-model to laboratory experiments.

The performance of the DUROS-model is evaluated with the predicted profiles in figure 5.3 and erosion amounts and dune retreats in table 5.2. The Brier Skill Score (BSS) on profile evolution is also added in the table.

Model performance

In general, the DUROS-model predicts for all simulated experiments a too gentle coastal profile. This profile extends too far in seaward direction. The run-up zone that is not taken into account in the DUROS+ model seems to contribute to the differences between predicted and measured profiles. The effect for small scales is more than for large scales. The predicted and measured erosion amounts for all experiments are plotted in figure 5.4 and 5.5. The performance, in terms of BSS is from small-scale to large-scale resp. 0.32, 0.38, 0.61 and 0.87. In line with the expectations (from previous page), the model performs quite well for large-scale, but performs insufficient for small-scale experiments.

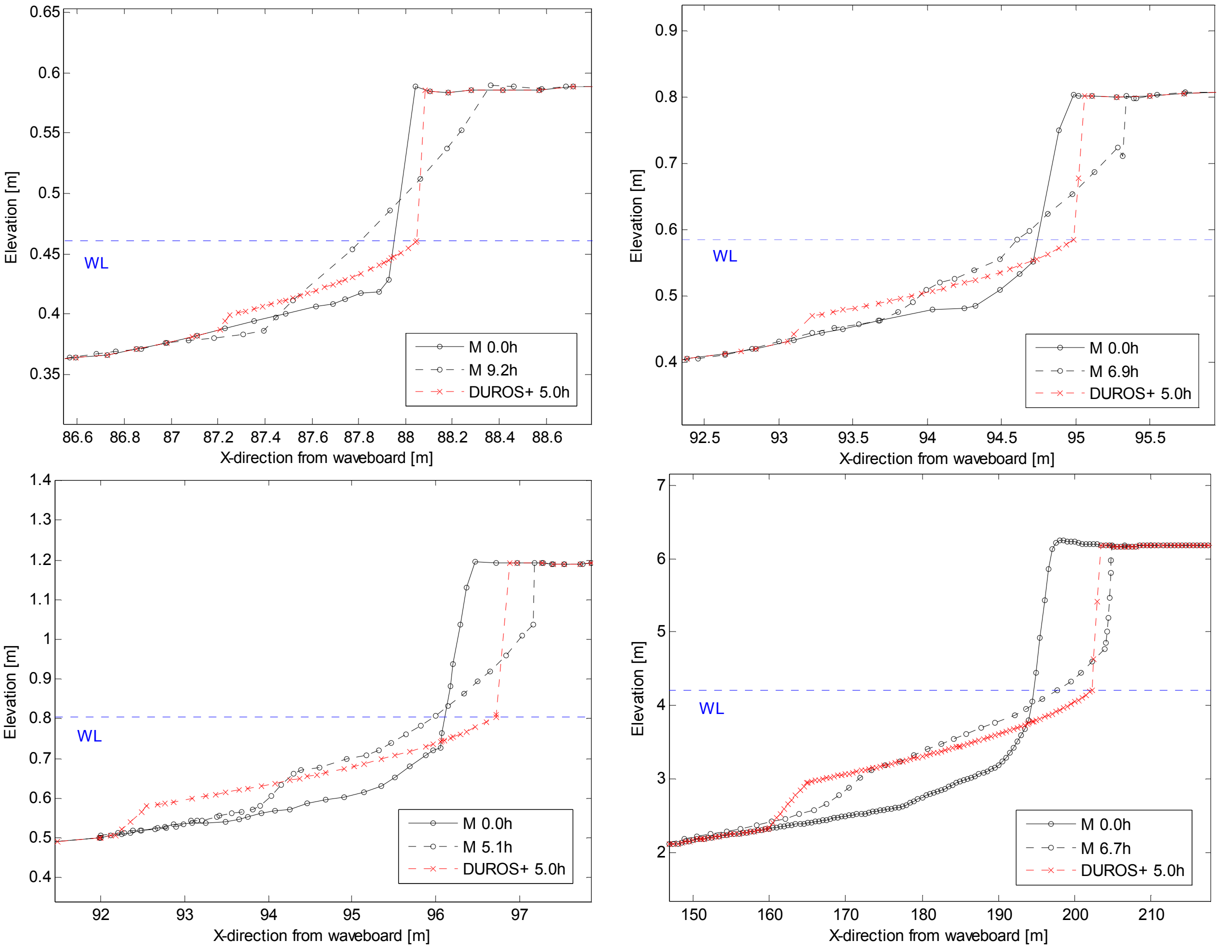


Figure 5.3: Predicted post-storm profiles on laboratory scale with the DUROS-model. The red dashed line represents the (to laboratory scale converted) DUROS prediction, the black dashed line is the laboratory measurement, the blue dashed line is the water line and the black solid line is the initial profile. Upper left panel: Laboratory experiment test-111 on scale 84. Upper right panel: Test-101 on scale 47. Lower left panel: Test-121 on scale 26. Lower right panel: Test-1 on scale 5.

Detailed analysis per depth scale

The DUROS-model shows for the depth scale n_d=84, an erosion amount underestimation of about 43%. The prototype dune retreat of 0.248m is only 19% of the actual dune retreat (see table 5.2). The predicted profile with DUROS+ has a too broad seaward extend of the equilibrium profile, the profile slope is too gentle and the profile above storm surge level does not resemble the measured profile. The differences in predicted and measured profile above the storm surge level, can possibly be related to not proper modelling of the run-up zone, the run-up heights in small-scales are approximately $n_d^{0.56}$ too large (see section 3.4).

The DUROS-model underestimates the dune erosion for test-101 on depth scale n_d=47 by 32%. The dune retreat on prototype scale is with 0.28m only 36% of the actual dune retreat. The seaward extend of the equilibrium profile is broader than the seaward extend in laboratory. The slope of the profile is too gentle and the dune foot, which is set at the storm surge level in DUROS, is too low. The run-up effect discussed in section 3.2 also seems to be very important on scale n_d=47.

Scale	Experiment	Measured erosion volume [m^3/m]	Predicted erosion volume [m^3/m]	Measured dune retreat [m]	Predicted dune retreat [m]	BSS [-]
84	Test-111	0.015	0.009	0.296	0.048	0.32
47	Test-101	0.055	0.039	0.39	0.11	0.38
26	Test-121	0.22	0.21	0.77	0.45	0.61
5	Test-1	13.2	14.2	8.3	6.8	0.87

Table 5.2: DUROS+ performance: Measured and predicted erosion volume and dune retreat.

On depth scale n_d=26, the DUROS-model underestimated the erosion amount above storm surge level with 7%. The predicted prototype dune retreat is with 0.32m only 58% of the actual dune retreat. The seaward extend of the profile is too broad and the profile slope is too gentle. The predicted dune foot on depth scale n_d=26 is too low.

The DUROS-model overestimated the dune erosion above storm surge level with 8% for the depth scale of n_d=5. The model was calibrated on large scale experiments among which experiment test-1. The predicted prototype dune retreat is slightly smaller. With 6.8m the predicted dune retreat is 83% of the actual dune retreat. The length of the measured and predicted profiles is the same, but the predicted profile is too gentle. Also the seawards shift of the equilibrium profile in the DUROS model is too far. The predicted dune foot is for the depth scale n_d=5 still too low.

All experiments
In figure 5.3, the performance of the DUROS-model is averaged on four scales, depth scale n_d=5, depth scale n_d=26, depth scale n_d=47 (46.6-47) and depth scale n_d=84 (83.6-84). The error bar gives the variance in performance for the different experiments.

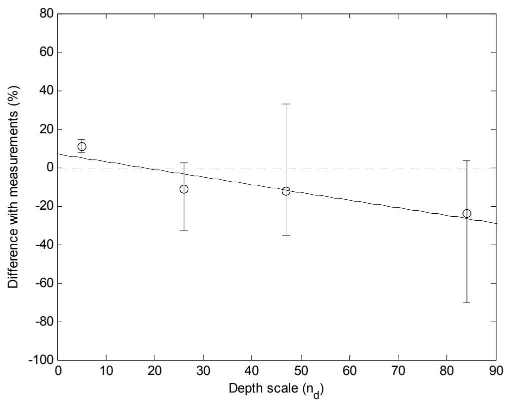


Figure 5.4: DUROS+ performance expressed in erosion amount above storm surge level. The predicted erosion amounts above storm surge level are compared with the measured erosion amounts and averaged per depth scale (circles). The error bar represents the variance in DUROS performance for the different experiments (see appendix A-3).

Figure 5.4 shows that the DUROS-model performs quite inconsistent (big range) for small-scale experiments and consistent for large-scale experiments (40-80% compared to 5%). The big variety makes it very difficult to extract a clear trend for the performance on different scales. When comparing the average performances on different scales, the DUROS-model overestimates the erosion amount for scales larger than 26 and an underestimates the erosion amount for scales below 26. The measured and predicted erosion amounts of all experiments are plotted in figure 5.5. The figure shows that the DUROS+-model underestimates the erosion amount for about 70% of the experiments.

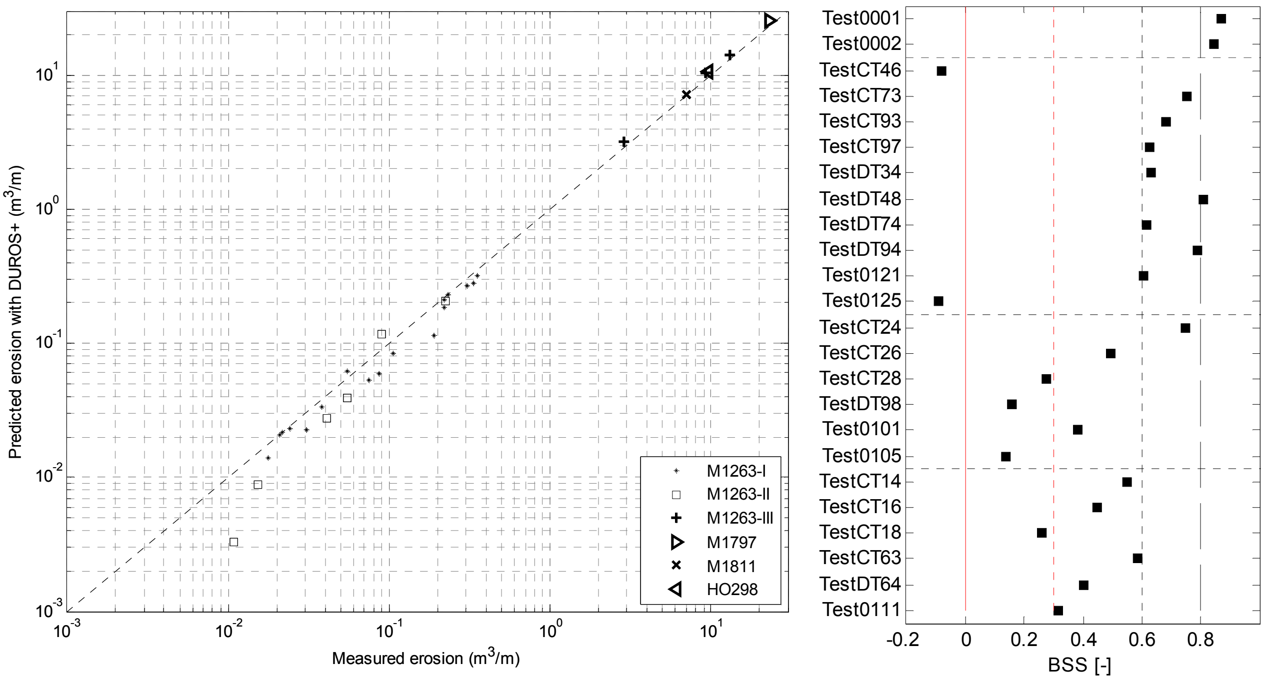


Figure 5.5: Result of DUROS+ verification with M1263-I (n_d=5), M1263-II (n_d=5), M1263-III (n_d=5), M1797 (n_d=2), M1811 (n_d=4) and HO298 (n_d=5) experiments. Left panel: Measured erosion volumes are plotted against predicted erosion volumes with DUROS. Right panel: BSS score of all experiments, in which upper row is large-scale, second row is scale 26, third is scale 47 and lower is scale 84.

5.2.3 Development of a renewed model: DUROS research model.

The present DUROS-model that was evaluated in section 5.2.2 performs with regard to profile development very poor in the region above the storm surge level. The assumed dune slope of 1:1 seems to disagree with the run-up shape that can be noted when examining different laboratory profiles (chapter 3). Figure 3.10 shows that the wave run-up on different lab scales strongly influences the (prototype) dune erosion amount. Because erosion volumes on various scales do not correspond, this run-up effect is introduced in the model.
The comparison of the DUROS-model with the laboratory experiments showed that the model underrates the slope of the (erosion) profile for each depth scale. In this section, the general equilibrium profile is based on (only) large-scale experiments (see appendix A-1.2).

The DUROS research model contains the next two assumptions:

- A new general equilibrium prototype profile was created with large-scale experimental results and the distortion relation of Vellinga (1986), and
- Run-up zone: A run-up zone is introduced that is dependent on the wave conditions and foreshore slope.

(See appendix A-1.2, for detailed model conversion).

Run-up zone
During analysis of lab experiments in chapter 3, the run-up bed slope was found to be very similar for the experiments on the same scale. The slopes on various scales could be related with the distortion relation. With relation (3.5) a prototype slope of β=0.067 was found. The run-up height was reproduced by a new run-up formula(3.10). The run-up zone is schematized below:

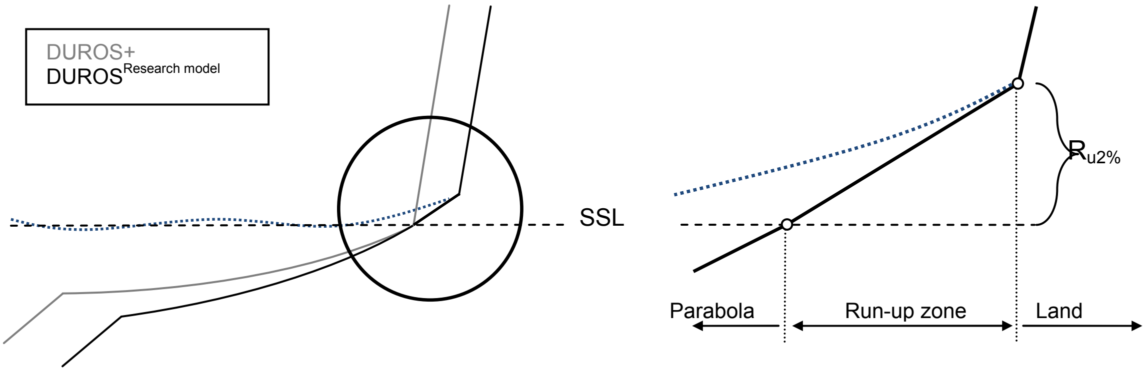


Figure 5.6: Run-up zone in the DUROS research version.

The new DUROS post-storm profile is based on four elements (see figure 5.6);
- (1) a landward dune slope (1:1),
- (2) a run-up zone, slope (1:15) and height obtained with equation (3.10),
- (3) a new parabolic 'equilibrium' profile, and
- (4) a seaward slope (1:12.5) at the end of the equilibrium profile until the initial coastal profile.

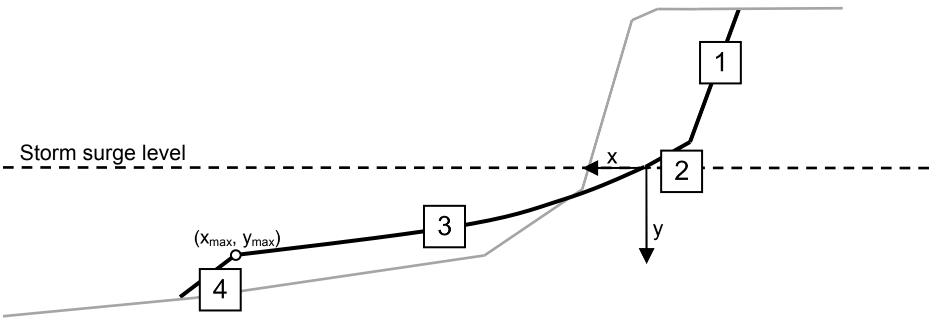


Figure 5.7: Four elements of DUROS research version: Landward slope (1), run-up zone (2), parabolic profile (3) and seaward slope (4).

The new model is calibrated with experiments M1263-III, M1797, M1811 and HO298. The calibrated model has a parabolic profile of 160m. The new model is applied to the 4 selected experiments. The results are shown in table 5.3 (see also appendix A-9).

	Erosion volume [m^3m^{-1}]			Dune retreat [m]			Brier Skill Score [-]	
Exp.	Measured	D+	D_{RV}	Measured	D+	D_{RV}	D+	D_{RV}
Test-111	0.015	0.009	0.018	0.296	0.048	0.350	0.32	0.91
Test-101	0.055	0.039	0.065	0.39	0.11	0.54	0.38	0.86
Test-121	0.22	0.21	0.28	0.77	0.45	0.96	0.61	0.85
Test-1	13.2	14.2	12.7	8.3	6.8	6.7	0.87	0.91

Table 5.3: Model performance DUROS (D+) and DUROS research version (D_{RV}).

Compared to the current model, the model performance of the research version is significantly better. The BSS increases up to approx. 0.9 for all experiments. The model slightly overrates the erosion amount and the dune retreat for all scales.

5.3 Comparison of XBeach with laboratory tests

5.3.1 Approach

In the next section, the laboratory experiments are tested with the XBeach-model with default settings (see appendix A-2). In section 5.3.3, the model is calibrated by scaling specific input parameters in the model. Afterwards, the calibrated XBeach-model is tested against all laboratory experiments.

Verification	Testing the default model against lab experiments	Section 5.3.2
Calibration	Adjusting the model settings to improve model performance	Section 5.3.3
Validation	Testing the model with adjusted settings against lab experiments	Section 5.3.4

5.3.2 Verification with default settings

In this section, the XBeach-model is tested on the laboratory experiments with default settings. The research program distinguishes experiment in two different wave flumes on four different depth scales, n_d=5 (Deltaflume), n_d=26, n_d=47 and n_d=84 (Wind-flume). The performance of the model on experiments test-111, test-101, test-121 and test-1 are plotted in figure 5.8.

Model performance

Generally, the dune erosion amount was overestimated, the simulated dune foot is too low and the slope in the run-up (or swash) zone is too gentle. The absence of a smooth transition from swash zone to dune is probably caused by a disordered demand/supply ratio of sediment in the swash zone: the transport capacity of nearshore hydrodynamics is larger than the supply of sediment from the dune. It was expected that the supply of sediment from the dune was underestimated and the demand of sediment by nearshore hydrodynamics was overestimated. The parameters in the avalanche algorithm could be scaled to increase the (simulated) supply of sediment and some sediment transport parameters in XBeach could be scaled to decrease the (simulated) demand for sediment.

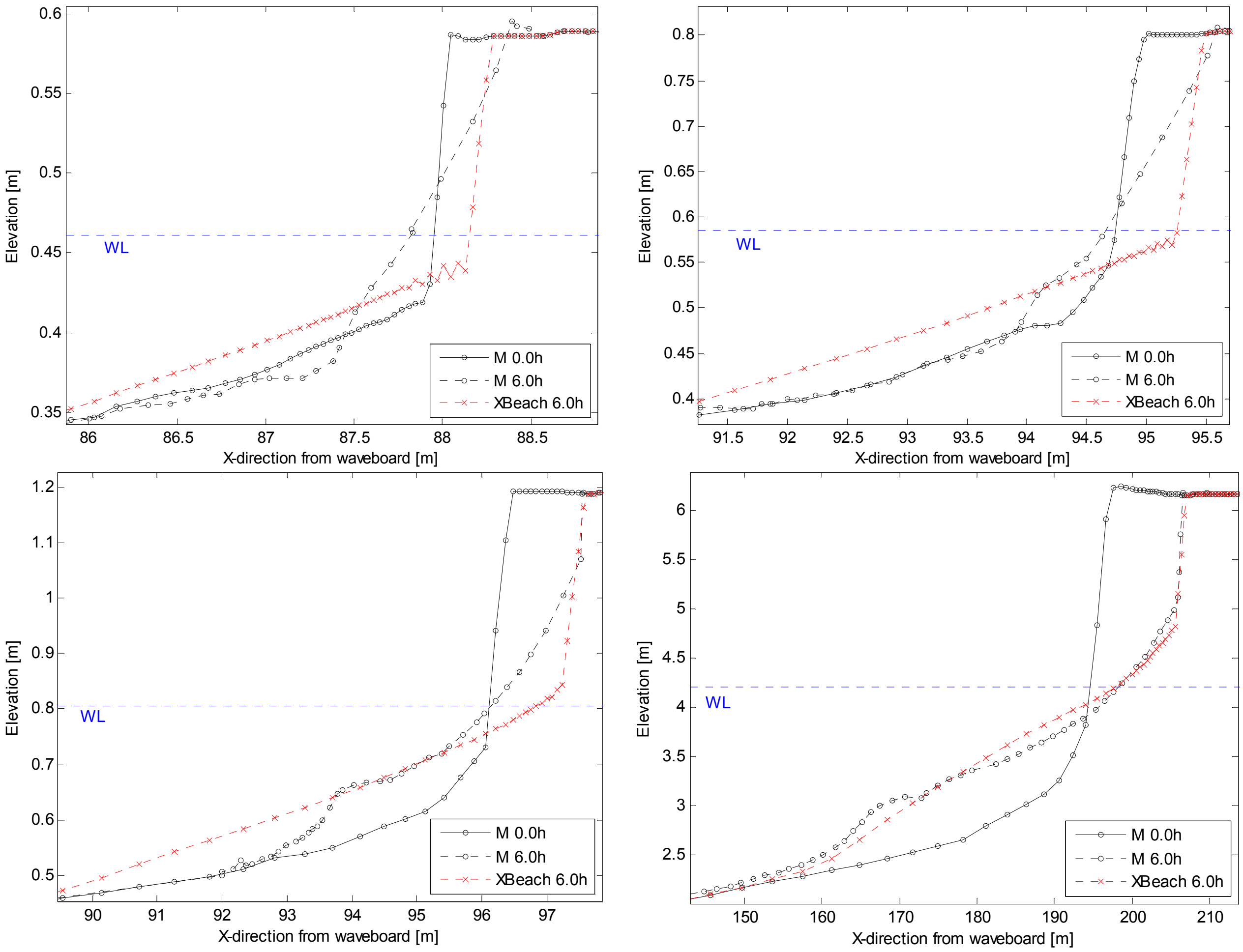


Figure 5.8: Predicted post-storm profiles on laboratory scale with the XBeach-model. The red dashed line represents the XBeach prediction, the black dashed line is the laboratory measurement, the blue dashed line is the water line and the black solid line is the initial profile. Upper left panel: Laboratory experiment test-111 on scale 84. Upper right panel: Test-101 on scale 47. Lower left panel: Test-121 on scale 26. Lower right panel: Test-1 on scale 5.

Detailed analysis per depth scale

The XBeach simulation of the n_d=84 experiments test-111 shows an overestimation of the erosion amount. The nearshore profile development appears to be much more than is measured during the experiment, which is probably effect by an overestimation of the offshore transport rate. An error emerges at the dune foot. The not proper modelling of the upper swash zone is probably effected by the supply of sediment from the dune that is modelled with the avalanche algorithm. The BSS of the simulation is -0.3, which is very bad.

The simulation on depth scale n_d=47 shows for the erosion amount an overestimation of 70%. The dune foot error also seems to appear for scale n_d=47. The modelled offshore sediment transport is too large compared with the measurements. The performance of the model on scale n_d=47 is -0.18.

The XBeach-model seems to perform quite good for the depth scale of n_d=26, according to the Brier Skill Score method. The dune foot emerges above the storm surge level, which is in line with the measurement observations. The simulated profile development in seaward direction is two times larger than the measurements.

Scale	Experiment	Measured erosion volume [m^3/m]	Predicted erosion volume [m^3/m]	Measured dune retreat [m]	Predicted dune retreat [m]	BSS [-]
84	Test-111	0.017	0.027	0.31	0.24	-0.30
47	Test-101	0.066	0.112	0.57	0.50	-0.18
26	Test-121	0.32	0.43	1.12	1.12	0.76
5	Test-1	17.6	18.3	9.9	10.1	0.98

Table 5.4: XBeach performance: Measured and predicted laboratory erosion volume and dune retreat after 6h simulation time.

Note: For model verification, the measurements times for DUROS (table 5.2) and XBeach (table 5.4) were chosen differently. For DUROS the times closest to 5h prototype are taken. For XBeach the last measurements were taken.

The simulation of the depth scale n_d=5 shows the best result. The model performs excellent for both profile development and dune erosion (this is also logical, because the default settings are based on calibration with depth scale n_d=6). Table 5.4 provides an overview of the model performance for the different laboratory scales.

5.3.3 Calibration of XBeach settings

In the previous section, it was found that the (default) XBeach-model performs insufficient for a small-scale laboratory experiment. In this section, the model input parameters are calibrated. Insights gathered from the analysis of the experimental data (chapter 3), the model description (section 4.3), the sensitivity analysis (section 4.4) and a parameter sensitivity analysis (not included), are used for the calibration. In the calibration, three scenarios can be distinguished;

1) Proposed numerical parameters,
2) The effect of near-bed turbulence, and
3) The scaling of the wet slope parameter.

Calibration step			Content	
1	Numerical parameters	Hydrodynamic	Wave breaking coefficient γ (not investigated in detail)	p53
		Morphodynamic	Parameters dzmax, hswitch, hmin and eps	p56
	Critical flow velocity for sediment transport		u_{cr} formulation (not investigated in detail)	p58
2	Near-bed turbulence		Turbulence intensity	p60
3	Run-up slope		Wetslp parameter	p60

Table 5.5: Approach for parameter calibration of XBeach.

1) Adjusting numerical parameters of the XBeach model

In this section, the hydrodynamic model and morpodynamic model are tested for scale applicability. For that, numerical parameters have to be adjusted.

Testing the dynamic similarity of the hydrodynamic model

First the XBeach-model is tested for hydrodynamic scalability. The hydrodynamics can be scaled according to the Froude relation (from section 2.5):

$$n_H = n_L = n_d = n_T^2 = n_t^2 = n_u^2 = n_v^2 \tag{5.2}$$

The characteristics of an arbitrary experiment, experiment CT14 (n_d=84), are used for testing the hydrodynamics. For this purpose the bathymetry and the wave input are taken. Table 5.6 gives an overview of the settings that need to be scaled (with scaling factor S_f) to meet the Froude criterion.

	Wave board		Bathymetry			Time
Scale factor	H_{m0}	T_p	X-grid	Y-grid	zs0	Simulation time
S_f (1-30)	S_f	$\sqrt{S_f}$	S_f	S_f	S_f	$\sqrt{S_f}$

Table 5.6: Settings that need to be changed for testing the hydrodynamics model in XBeach, according to Froude.

Two virtual models are created with the characteristics of experiment CT14; a very small model n_d=150 and a relatively large model n_d=5. When the wave heights along the wave flumes of the two simulations are geometrically scaled, the simulations can be compared (after rescaling). Figure 5.9 shows the wave height dissipation in the two XBeach simulations.

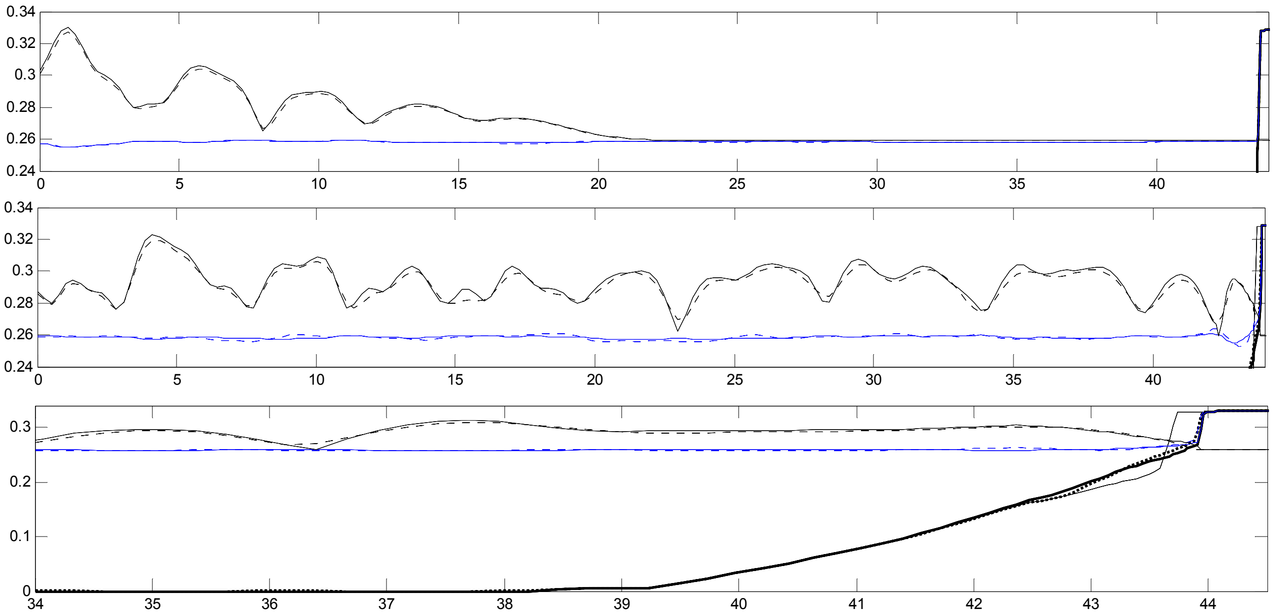


Figure 5.9: Testing the scalability of hydrodynamic model in XBeach. Simulated wave heights on two scales; scale n_d=150 (solid black line), and n_d=5 (dashed black line). Blue lines are the water levels. Upper panel: Wave heights and water levels after 20s simulation. Middle panel: Wave heights and water levels after 400s simulation. Lower panel: Wave heights, water levels and coastal profiles (fat lines) after 720s simulation.

As the figure shows, the simulated wave heights at scales n_d=150 and n_d=5 are pretty similar. The small differences in wave heights (of about 3%) can be dedicated to the decimation of the input signal and the effect of the coastal profile on the wave climate in de wave flume (the morphological parameters were scaled as suggested in table 5.7). The differences are assumed to be negligible. Therefore, it can be stated that the hydrodynamic model in XBeach scales according to Froude. Next, the hydrodynamic simulation is compared with the wave measurements.

Within the research program M1263 (I-III), several measurements were performed with regard to wave heights: interval and experiment-averaged measurements at several locations in the wave flume. In figure 5.10, the simulated and measured wave heights (H_s) are plotted for the four experiments test-1, test-121, test-101 and test-111. The runs were executed with default settings for wave breaking (γ=0.55, see appendix A-2).

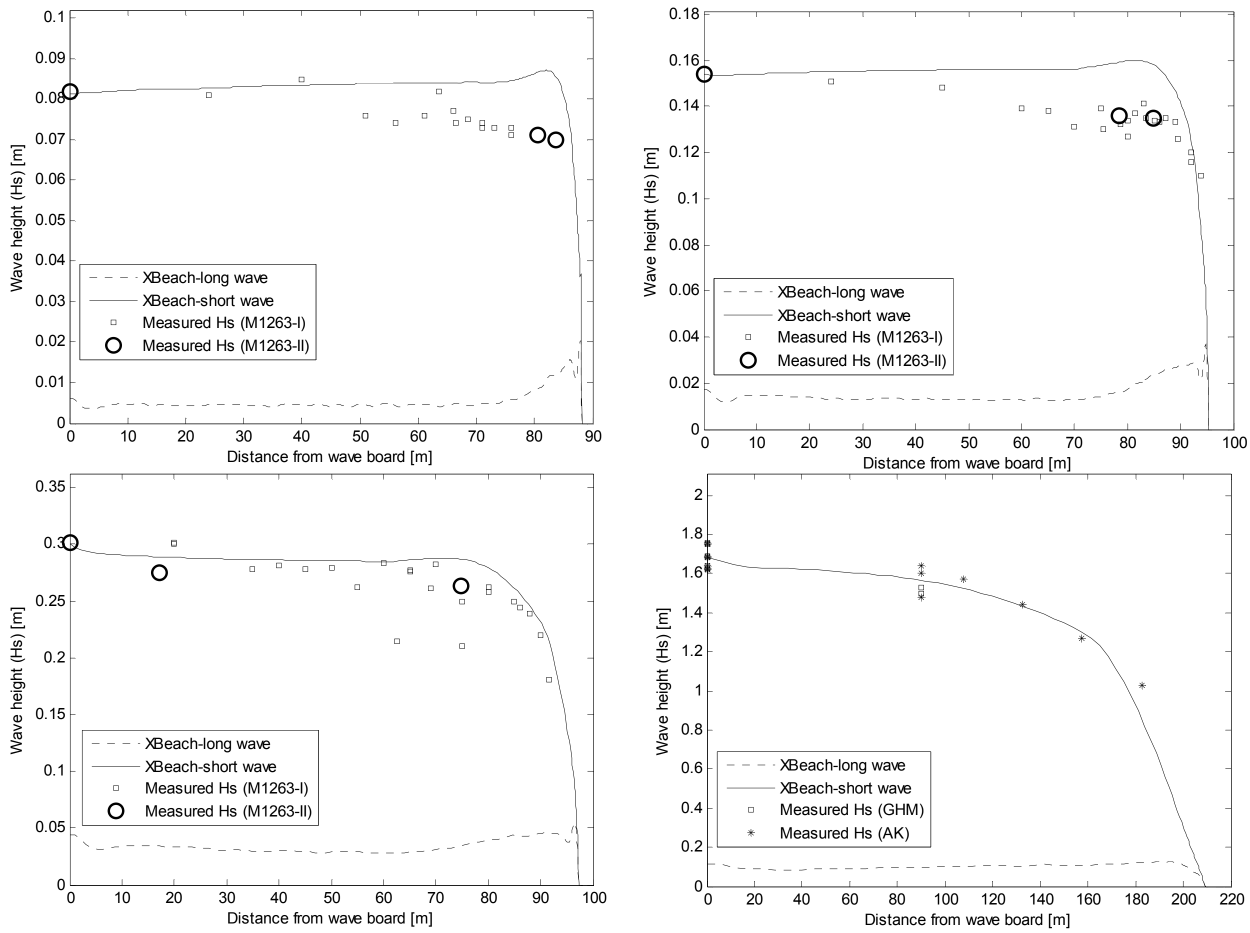


Figure 5.10: Average wave height simulated with XBeach at four depth scales: Upper left panel: depth scale 84. Upper right panel: depth scale 47. Lower left panel: depth scale 26. Lower right panel: depth scale 5.

The wave measurements indicate a continuous reduction of the wave height along the flume. In small-scale most waves break just in front of the dune (the measured wave height in front of the dune is slightly smaller than the wave height at the wave board). In large-scale, the wave height already starts to decrease about halfway the wave flume.

For small-scale experiments ($n_d \geq 26$), the simulated wave height slightly increases along the wave flume. When approaching the nearshore zone, the waves start to shoal until they break. In the large-scale experiment, the waves start to dissipate quite early because the coastal profile already starts at approx. 40m from the wave generator, resulting in a continuous decreasing wave height along the wave flume. The upper panels show that the model overestimates the foreshore wave heights for small-scale experiments ($n_d > 26$).

In XBeach, the probability of wave-breaking is computed by:

$$P_b = 1 - \exp\left(-\left(\frac{H_{rms}}{\gamma h} \right)^n \right) \quad (5.3)$$

In which, h is the water depth, γ (0.55) and n (10) are calibration coefficients (remark: do not confuse parameter γ with the breaker-index γ_b). Better agreement between measured and simulated wave heights at the scales 84, 47, 26 and 5 were obtained with values of resp. 0.3, 0.35, 0,38 and 0,52 for γ. At this stage, it was chosen to use the default wave-breaking coefficient (γ=0.55) for all simulations, because the differences are quite small (maximal 1cm on small scales and 10cm on large scales, that is about 15%).

XBeach parameter	Explanation	Process	Unit	Proposed scaling factor
dzmax	Maximum avalanche speed (see 4.3.2)	Avalanching	[$m^3s^{-1}m^{-1}$]	$S_f^{1.5}$
hswitch	Water depth at the interface from wet slope to dry slope (see 4.3.2)	Avalanching	[m]	S_f^1
hmin	Threshold water depth for concentration and return flow: Above a water depth of *hmin*, the Stokes drift is included	Limiter	[m]	S_f^1
eps	Threshold depth for drying and flooding: When the water depth exceeds *eps*, dry cells become wet. Cells need to be wet for sediment transport	Limiter	[m]	S_f^1

Table 5.7: XBeach parameters that are proposed for calibration: The maximum avalanche speed (dzmax) and the water depth for the wet/dry interface (hswitch) are parameters in the avalanche algorithm. The hmin parameter is a limiter for the return flow and the eps is a limiter for the water depth for drying/flooding. The proposed scaling factors for each parameter are based on their units.

Morphodynamic model

Waves induce water movement. When the water depth is small enough this disturbance will penetrate into the water column and results in shear stresses on the bed sediment. When the forces exceed the critical forces sediment starts to move. The sediment transport in XBeach is modelled with a depth-averaged advection-diffusion equation (see appendix A-5).
In section 4.3.2, the avalanche model was described. This algorithm simulates the release of sediment from the dune when waves 'hit' the dune face. It was suggested that the parameters in this model need to be calibrated when applying the model at different scales. With a parameter sensitivity analysis a selection of parameters is made that are expected to be scale dependent: *dzmax*, *hswitch*, *hmin* and *eps* (see table 5.7).

The maximum avalanche rate (*dzmax*) represents a volume of sediment (m^3) that is maximal avalanched per unit time (s) and meter (m). The proposed scaling of the selected parameters is based on the unit of the parameter. In an undistorted model, like XBeach, scaling can be performed according to Froude, so:

$$n_h = n_l = n_t^2 \tag{5.4}$$

Scaling the maximum avalanche parameter leads to (only when $n_t = n_{Tm}$):

$$n_{dz\max} = n_h n_l n_t^{-1} = n_h n_l n_h^{-0.5} = S_f^{1.5} \tag{5.5}$$

The unit of the other three parameters are all the same and are therefore scaled according to the scaling factor (S_f).

Testing the kinematic similarity in XBeach with the selected morphological parameters
According to Dean's undistorted modelling criteria (1985), similarity can be achieved when; 1) the model is geometrically undistorted (equal horizontal and vertical length scale), 2) hydrodynamics are scaled according to Froude similarity, 3) the fall speed parameter is similar on prototype and model, 4) the model is large enough to preclude significant viscous, surface tension and cohesive sediment effects so that the character of wave breaking is properly simulated and 5) bed material is sand (n_s=1) (Hughes, 1993). According to Dean (1985) and Hughes (1993) using an undistorted model, the scaling of the morphological parameters should be performed by:

$$n_{Tm} = n_h^{0.5} \quad (5.6)$$

$$n_{ws} = n_l^{0.5} \quad (5.7)$$

In which n_{Tm} represents the morphological timescale factor and n_{ws} the scaling factor of the sediment fall velocity. The correctness of the scaling factors was confirmed by Fowler and Hughes (1991). The previous simulation is used, because the morphological scaling and the hydro dynamical scaling was performed at the same time.

In the simulation at scale n_d=150, a sediment size of D_{50}=150μm (w_s=0.0154) was chosen. The sediment in the n_d=5 simulation was D_{50}=637μm (w_s=0.0846). Figure 5.11 shows that the profiles are quite different for the simulations at the two scales. The differences can be explained by the lacking sensitivity of XBeach to the sediment sizes (see chapter 4).
A simulation on scale n_d=5 with a smaller sediment size (~250μm) shows a better agreement with the n_d=150 simulation. It is possible that XBeach underrates the effect of smaller sediment sizes (this is also observed in section 4.4.2).

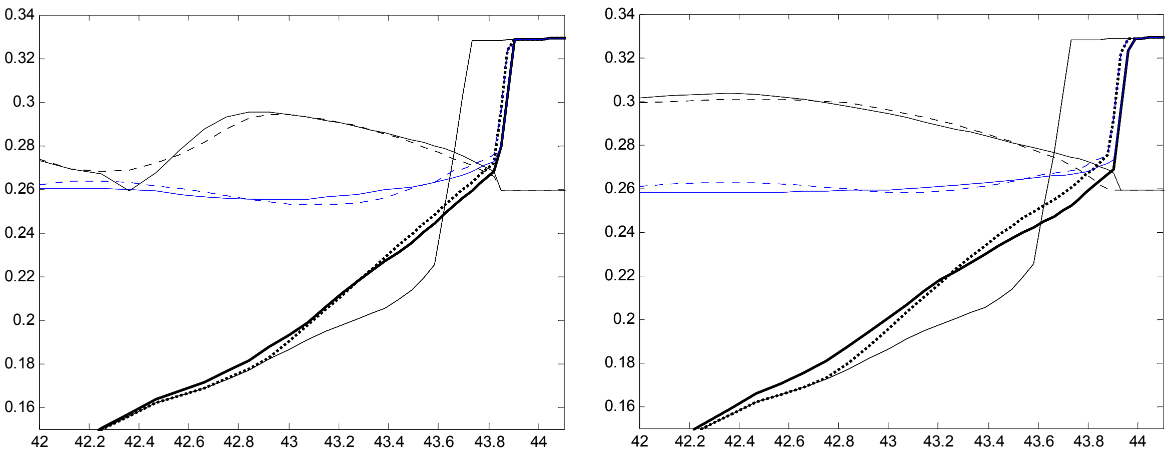


Figure 5.11: Testing the morphologic model in XBeach. Profile development of simulations on two (virtual) scales: Scale n_d=150 (fat solid black line) and n_d=5 (fat dotted line). The blue solid and dashed lines are the water levels for resp. scale 150 and 5. The black lines are the water heights (H_s). Left panel: Profile development after 400 seconds with sediment size 150μm. Right panel: Profile development after 720 seconds with sediment size 637μm.

Model performance for calibrated numerical parameters
In section 5.3.2 it was found that the model performs insufficient for small-scale experiments. Therefore, the effect of the different calibration iterations is discussed only for small scale experiments.
In the first step the avalanche parameters, maximum erosion speed and the water depth at the dry/wet interface, and the sediment transport limiters, *hmin* and *eps*, are changed. The scaling is

performed according to their unit (see table 5.7). The profiles on small scales (n_d=84-26), show a general overestimation of the erosion amount (see table 5.8). The erosion amounts are in fact more than for the default scenario, but the instability at the dune foot seems to be fixed. In figure 5.12, the measured and simulated sediment transport rates in the experiment test-111 are plotted for interval 0-1.0h and 1.0-6.0h.

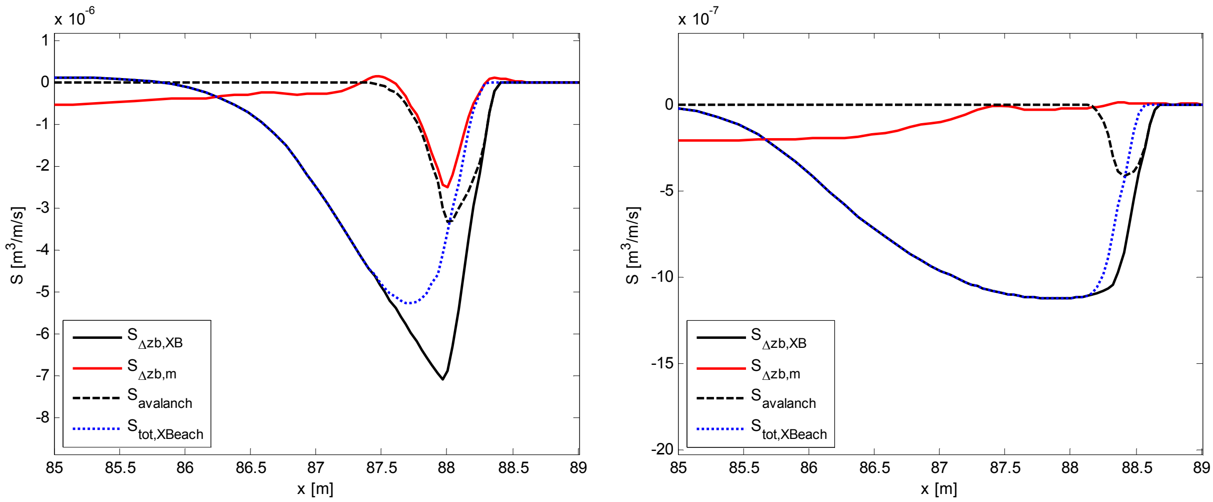


Figure 5.12: Sediment transport rates in experiment test-111. The sediment transport from simulated profiles (fat black lines), the sediment transport from measured profiles (fat red lines), the sediment transport from avalanching (black dashed lines) and the sediment transport from bed-and suspended load are plotted ($S_{tot,XBeach}$) (blue dotted lines). Left panel: Average transport rate at the start of the simulation till 1h. Right panel: Average transport rate from 1h till 6h simulation.

The transport rate in the first part of the simulation is about 2 times larger than the measured rate. The measured rate in the second part of the experiment is almost zero. The model strongly overrates the sediment transport in the second part (1.0-6.0h). The right panel shows that the erosion rate is dominated by the transport capacity of the nearshore hydrodynamics (bed- and suspended load).

Calibration of the critical flow velocity

The overestimation of the erosion rate is expected to be caused by the overestimation of the actual effective flow velocity. The effective flow velocity is the total flow velocity (drag forces) from hydrodynamics lowered with the critical velocity (inertial forces). The total flow velocity can be described by the Eulerian mean and the infragravity (u^E) in combination with near bed short wave orbital flow ($u_{rms,2}$) (see appendix A-5). The effective velocity is defined as:

$$u_{eff} = \left(\left(|u^E|^2 + 0.64 u_{rms,2}^2 \right)^{0.5} - u_{cr} \right) \tag{5.8}$$

In which the short wave orbital flow equals:

$$u_{rms,2} = \left(u_{rms}^2 + 1.45 k_b \right)^{0.5} \tag{5.9}$$

With k_b the bore-averaged near-bed turbulence energy.

The forcing velocities (u_{tot}) are lowered with the critical depth-averaged velocity for initiation of motion (equation (5.8)). So, only the difference between total and critical flow velocity contributes to the equilibrium sediment entrainment. If the actual effective flow velocity is overrated, this can either be caused by an overestimation of the total flow velocity or by the underestimation of the critical flow velocity. In figure 5.13, the critical velocity and the total flow velocity with its components are plotted.

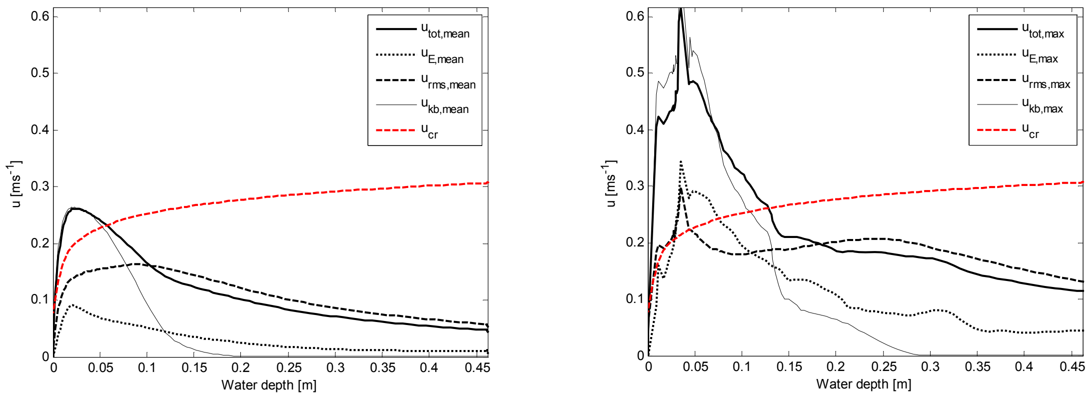


Figure 5.13: Depth-averaged flow velocities for experiment test-111. The red dashed line is the critical velocity for initiation of motion (Van Rijn, 1984). The fat black line is the total flow velocity combining Eulerian mean (dotted line), orbital velocity (dashed line) and the turbulence induced velocity (thin black line). Left panel: Mean depth-averaged velocities. Right panel: Maximum depth-averaged velocities.

An explanation for a general overestimation of the effective flow velocity at small-scales can be found in the used formulation of the critical depth-averaged velocity. The applied formulation of Van Rijn (1984) (see appendix A-5), is a simplification of the (more) general critical depth-averaged velocity equation for initiation of motion of Van Rijn that uses the Shields curve to determine no motion/motion and motion/suspension transitions. Van Rijn (1993) distinguishes initiation of motion into initiation of *motion* and initiation of *suspension* (see figure A-5.2). In figure 5.14, the other critical velocities are included.

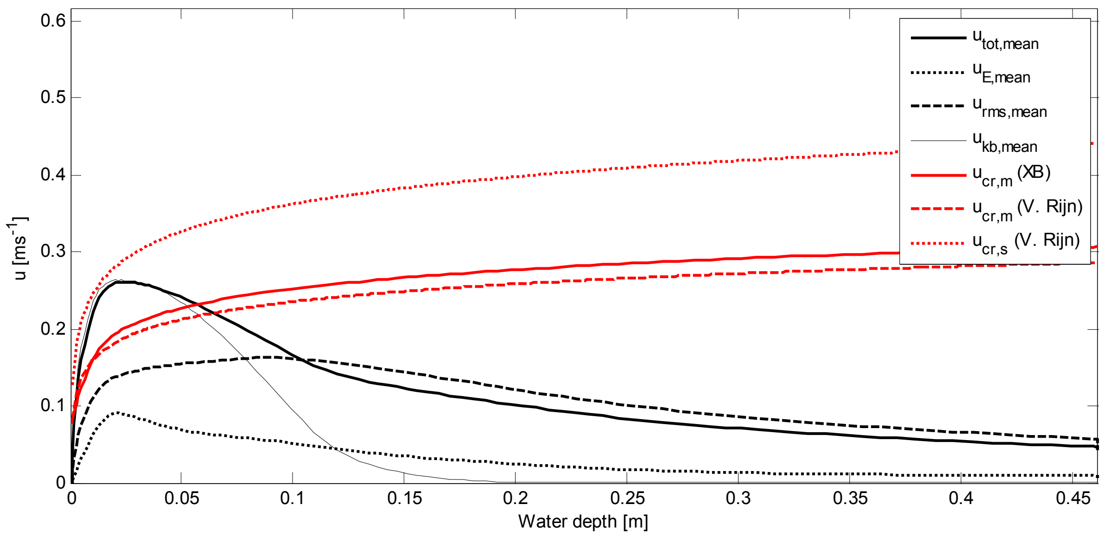


Figure 5.14: Mean depth-averaged flow velocities for experiment test-111. The red solid line is the critical velocity for initiation of motion (Van Rijn, 1984). The red dashed and red dotted lines are critical velocities for initiation of motion and suspension (Van Rijn, 1993). The fat black line is the total flow velocity combining Eulerian mean and infragravity (dotted line), orbital velocity (dashed line) and the turbulence induced velocity (thin black line).

Assumed is that the Van Rijn (1993) relations better represent the actual initiation of motion. The critical velocities in figure 5.14 show that in XBeach, the initiation of *motion* is overestimated with about 7% and underestimated with 44% for the initiation of *suspension*. Figure 5.12 (right-hand panel) shows that for this small-scale experiment, the transport rate is dominated by transport driven by hydrodynamics (bed load and suspended load). It is expected when linking bed load and suspended load to separate critical velocities, a better agreement with the measurements will be gathered. It is recommended to change this in the XBeach code:

$$C_{eq}=\frac{A_{sb}}{h}\left(\left(|u^E|^2+0.64u_{rms,2}^2\right)^{0.5}-u_{cr,m}\right)^{1.5}+\frac{A_{ss}}{h}\left(\left(|u^E|^2+0.64u_{rms,2}^2\right)^{0.5}-u_{cr,s}\right)^{2.4} \quad (5.10)$$

And

$$A_{ss}=\frac{0.0168D_{50}\rho_s D_*^{-0.6}}{\left((s-1)gD_{50}\right)^{1.2}} \quad (5.11)$$

First tests with a new XBeach program with relations 5.10 & 5.11, showed that the performance for small-scale increases up to BSS=0.8 (performance on large scale stays the same). Note: all calibration steps are done with the former sediment formulation (in which one critical velocity is used).

2) Calibration of the near-bed turbulence

Figure 5.13 (left hand panel) indicates that the near-bed turbulence energy is dominant for the transport rate in the simulation of small scale experiments. It was hypothesised that the near-bed turbulence is overrated for small-scale experiments, by not proper scaling of turbulence (by XBeach). The second scenario implies excluding the turbulence induced flow velocity from the total flow velocity, so equation (5.9) becomes:

$$u_{rms,2}=u_{rms} \quad (5.12)$$

(For detailed description of k_b, see Van Thiel de Vries, 2009)

	Erosion volume [m^3m^{-1}]					Brier Skill Score [-]			
Exp.	Measured	**0**	**1**	**2**	**3**	**0**	**1**	**2**	**3**
Test-111	**0.017**	0.027	0.074	0.034	0.024	-0.30	-4.03	-0.01	0.43
Test-101	**0.066**	0.112	0.224	0.128	0.093	-0.18	-3.14	-0.20	0.45
Test-121	**0.32**	0.43	0.70	0.48	0.38	0.76	0.02	0.65	0.93
Test-1	**17.6**	18.3	18.3	14.72	14.9	0.98	0.98	0.89	0.89

Table 5.8: Model performance for scale experiments; default scenario (0), numerical parameters (1), turbulence (2) and the wet slope parameter (3).

The results can be found in appendix A-6. Excluding the turbulence factor, results in half of the erosion amounts for small scales. The dune retreat is for all scales in fairly good agreement with the measurements. The model performs poor for small-scales (n_d>26) (BSS of approx. 0.0). For scale n_d≤26, the model (still) performs excellent. Note that for experiment test-1, the model performance decreases. Therefore, it is recommended to apply this change only for small-scale experiments.

3) Calibration of the avalanche parameter; wetslp

The simulated profiles from the previous scenarios show that the model underrates the slope above the surge level for small-scale experiments. These small-scale models are in fact distorted laboratory models of the prototype reference profile (Vellinga, 1986). When scaling is performed according to Vellinga, the initial laboratory profiles become steeper with a smaller laboratory scale. In section 3.3 and section 5.2.3, the slope of the run-up zone is found to be strongly correlated to the laboratory scale on which the experiment was performed.

The critical slope in a wet environment is dependent on the sediment size. Because the sediment size is similar in the four different experiments, the different run-up slopes cannot be explained by the (physical) critical wet slope. Probably, another physical process determines the slope of the run-up zone. This was not investigated in this study.

The proposed scale factor for the run-up slope is described by relation (3.3). The XBeach-model was calibrated by changing the *wetslp*-parameter for simulations on different scales (do not confuse with the physical critical wet slope). In table 3.4 the values for the run-up slopes can be found that are used for the *wetslp* (for scales 84, 47, 26 and 5 they are resp. 0.21, 0.19, 0.17 and 0.11).
The simulation of the third scenario results in an improvement of the BSS from 0 till 0.43 for the small scale experiment test-111 and an improvement from -0.2 till 0.45 for experiment test-101. For both test-121 and test-1, the model performs excellent.

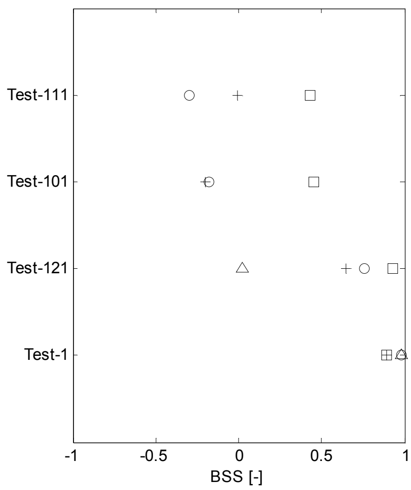


Figure 5.15: Model performance (BSS) during the calibration steps. Open circles are the default XBeach results. Open triangles represent the first step (numerical parameters in XBeach). The plus signs and the open squared sign represent step 2 (excluding turbulence) and 3 (adjusting the wetslp parameter) respectively.

At this point, no extra effort was spend on the further calibration. Figure 5.15, provides an overview of the model performance in the three calibration steps. The rather disappointing results of the small scale experiments (BSS≈0.5) are probably caused by the overestimation of the critical velocity for initiation of motion, the underestimation of the critical velocity for initiation of suspension and the not proper scaling of the turbulence.
In the next section, the XBeach-model with the settings of third scenario is validated with all available laboratory experiments.

5.3.4 Validation of XBeach

In this section, the XBeach-model with new settings is validated. Parameters *hmin*, *hswitch*, *eps*, *wetslp* and *dzmax* were scaled according their unit and the laboratory (depth) scale. Also, the turbulence induced flow velocity was excluded. The breaking parameter γ and the sediment concentration formula were not changed. In figure 5.16, the profiles after 6h simulation are shown for the experiments test-111, test-101, test-121 and test-1.

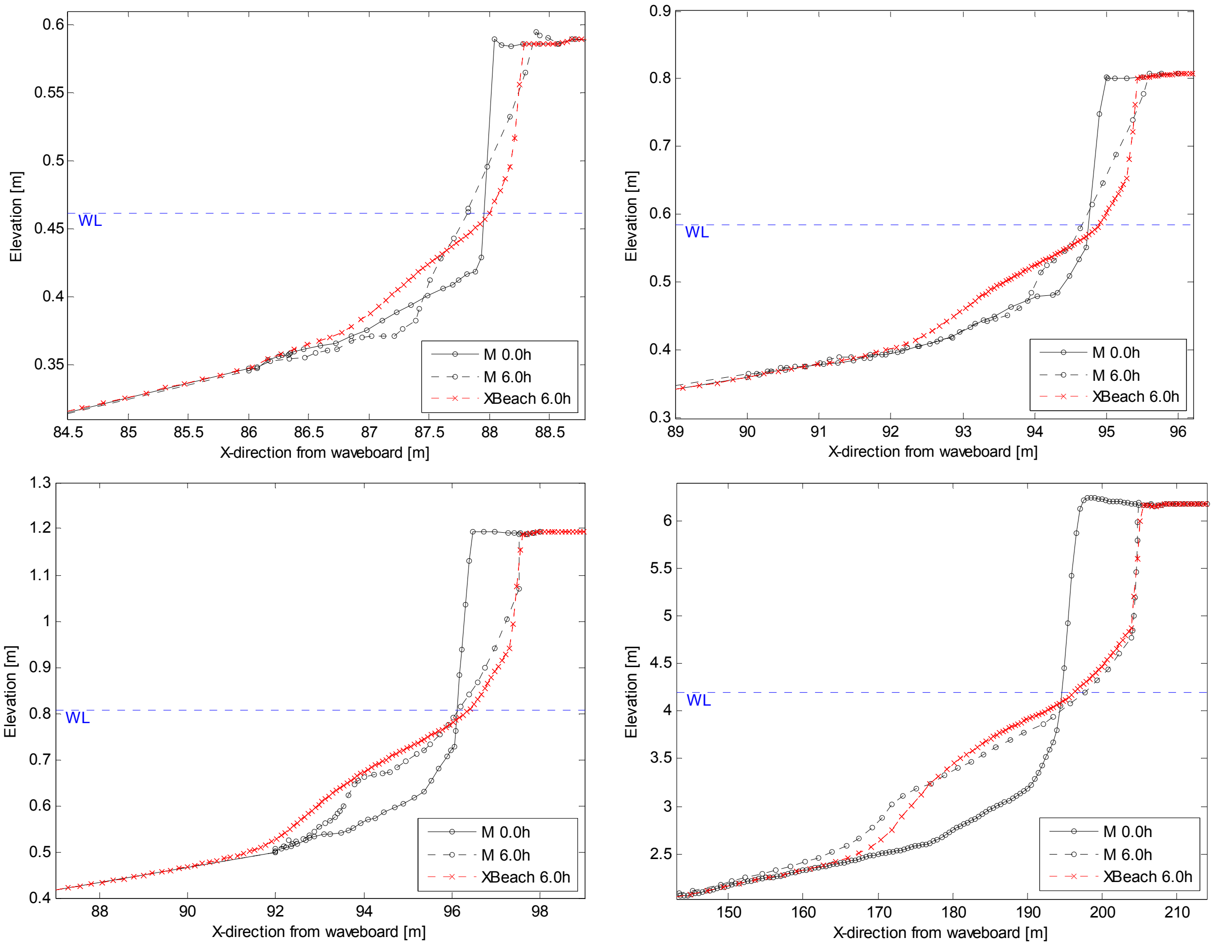


Figure 5.16: Predicted post-storm profiles on laboratory scale with the XBeach-model. The red dashed line represents the XBeach prediction, the black dashed line is the laboratory measurement, the blue dashed line is the water line and the black solid line is the initial profile. Upper left panel: Laboratory experiment test-111 on scale 84. Upper right panel: Test-101 on scale 47. Lower left panel: Test-121 on scale 26. Lower right panel: Test-1 on scale 5.

Compared to the results of the default simulation, the model with changed settings performs very well. Especially for small-scale experiments the improvement is enormous. The run-up zone still cannot be reproduced; this is probably caused by the fact that the run-up in the model is induced by the long wave, instead of a combination of long and short waves. The nearshore sediment transport is (still) overrated. This is probably caused by the overestimation of the effective flow velocities for motion and suspension that induce equilibrium sediment concentrations.

The results of the validation of the model with all experiments are shown in figure 5.17. The simulated and measured erosion amounts are plotted and the Brier Skill Score. On average the model overestimates the (post-storm) erosion amounts with 5% with a standard deviation of 23%.

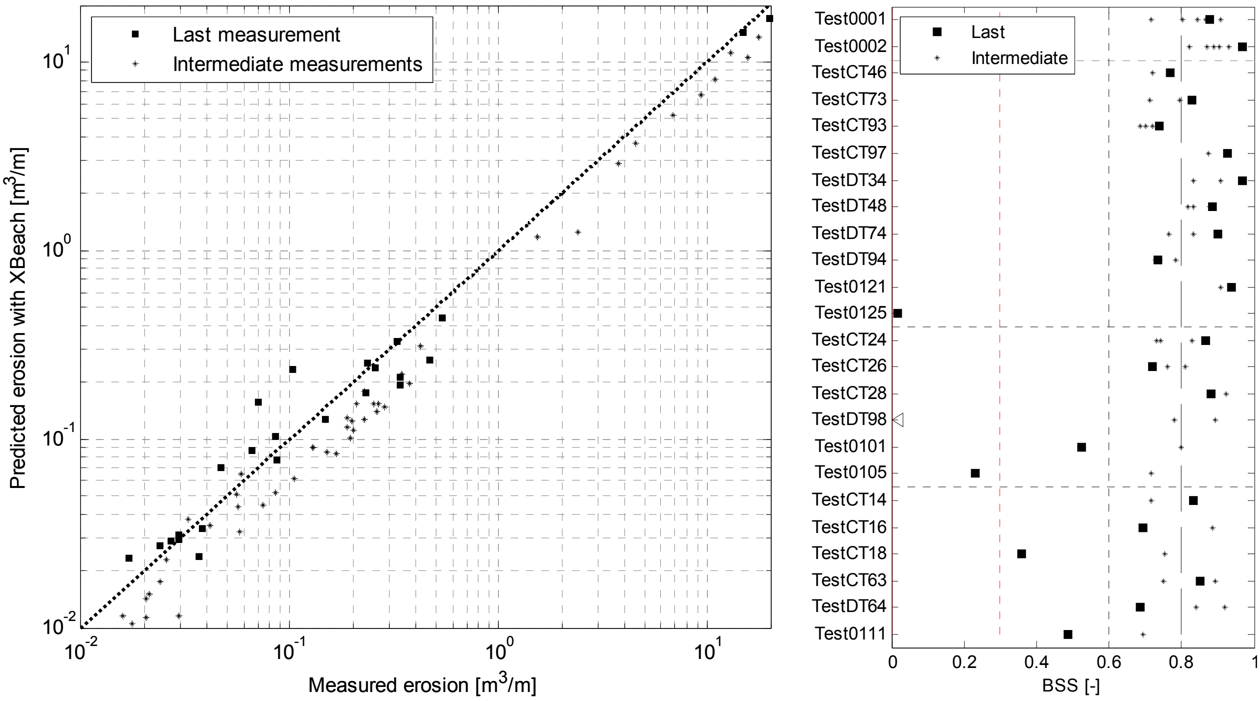


Figure 5.17: Result of XBeach validation with M1263-I, M1263-II, M1263-III experiments. Left panel: Measured erosion volumes are plotted against simulated erosion volumes with XBeach for intermediate measurement times and the last measurement time (at the end of the simulation). Right panel: BSS score of all experiments, in which upper row is large-scale, second row is scale 26, third is scale 47 and lower is scale 84. TestDT98 performs for the last point bad (<0.0).

Discussion

In this section experiments with other grain sizes are tested. In section 5.3.3, it was hypothesised that the overestimation of the erosion rate in small-scale experiments is partly caused by underrating the critical velocity for initiation of suspension. The critical velocity u_{cr} (Van Rijn, 1993) decreases with smaller grain sizes (D_{50}). Hypothetically, the erosion rate in experiments with smaller grains is therefore better reproduced with the model, because the critical velocity for suspension in the model is closer to the actual critical velocity for suspension. In figure 5.18 the profile development for the BT13 (M1263-I) experiment is shown.

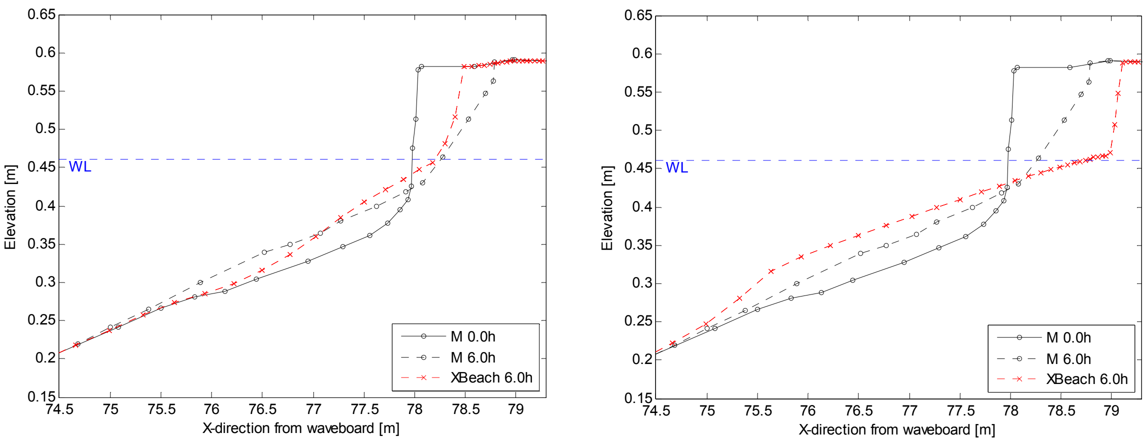


Figure 5.18: Profile development of experiment with smaller sediment (D_{50}=150μm). The red dashed line represents the XBeach prediction, the black dashed line is the laboratory measurement and the blue dashed line is the water line. Left panel: Without turbulence. The erosion amount is underestimated, 0.0466 to 0.0673 measured. The BSS for this experiment is 0.82 (0.48, 0.66 for intermediate measurements). Right panel:

With turbulence. The erosion amount is overestimated, 0.1275 to 0.0673 measured. The BSS for this experiment is 0.23 (0.89, 0.86 for intermediate measurements).

The simulations of the BT13 experiment show a better agreement with the measurements for resp. with and without the turbulence contribution (better than experiments with D_{50}=225µm). The BSS for scenario without turbulence improves from 0.0 to 0.82 and for the scenario with turbulence from -4.0 to 0.23. The other small-scale experiments with smaller sediment show similar performances. The fact that the bed load A_{sb} and the suspended load A_{ss} coefficients are also dependent on the grain size, it was recommended to further investigate the dependency on other sediment sizes.

5.3.5 Conclusion

The XBeach model is capable of predicting post-storm coastal profiles in a detailed manner. The nearshore hydrodynamic processes are modelled separately, which results in sediment transport and consequently dune erosion. The dune erosion is triggered by the (in-) stability of the dune face and the transport capacity of the nearshore hydrodynamics. The slumping of the dune face is a very complex process that can presently only be modelled by empirics.

The default XBeach-model performs well for large-scale experiments (n_d=5). These results are not surprising, since the model was calibrated with large-scale experiments (n_d=6). The model lacks performance for small-scale experiments. An error appears at the dune face. It is expected that the empirics within the avalanche algorithm are the reason for this. The sediment capacity of the near shore hydrodynamics is expected to be overrated in small scale experiments. This can be traced back to the larger seaward extent of the predicted post-storm profiles compared to the actual seaward extent in the experiment.

The calibration consists of three steps

1) An analysis of the parameters in the Xbeach-model resulted in a selection of four numerical parameters that were expected to be scale dependent: 1) the maximum avalanche speed, 2) the water depth at the interface from wet slope to dry slope, 3) the threshold water depth for concentration and return flow and 4) the threshold for drying and flooding. The proposed scaling of the four parameters was based on their units. For testing the kinematic similarity within the XBeach-model, an arbitrary experiment was taken that was scaled to two virtual experiments; a very small-scale n_d=150 and a large-scale n_d=5. The simulation showed that the sediment transport in XBeach scales not entirely in accordance with the scaling rules of Dean (1985) for undistorted models. It was hypothesised that the model underrates the effect of smaller sediment sizes.
   In the first scenario, the simulations of the selected small-scale experiments resulted in a general overestimation of the erosion amounts. The erosion amounts were even more overestimated than in the default simulations, but the errors in profile evolution near the dune foot was solved. An analysis of the erosion rates resolved that the overestimation of erosion amount was caused by an overestimation of the sediment transport from bed- and suspended load for small scales.

2) The sediment transport is a product of water movement and the concentration of sediment in the water column. The modelled sediment concentration is induced by the effective flow velocity defined as the total flow velocity (Eulerian mean, infragravity, short wave orbital flow and the bore-averaged near-bed turbulence) minus the critical velocity for initiation of motion. It was assumed that the near-bed turbulence, induced by wave breaking, is overrated in the small-scale experiments. Therefore, the turbulence contribution was excluded, resulting in the second scenario (with the settings of the first scenario). The

model simulation without the turbulence improved for small-scale experiments. The erosion amount decreased to twice the actual dune erosion. It was recommended to further analyse the scaling of turbulence, because total exclusion may not be realistic.
Both suspended load and bed load transport are simulated with the simplified equations of Van Rijn (1984). It was hypothesised that the bed load transport is linked to an overrated critical depth-averaged velocity for initiation of *motion* and the suspended load transport is linked to an underrated critical depth-averaged velocity for initiation of *suspension*. When the suspended transport is linked to a too low critical velocity in a calibrated experiment (or scale), the suspended transport on larger and smaller scales will resp. be underestimated and overestimated. This effect will be enforced when other sediment sizes were applied. It was recommended to change the formula for critical flow velocity.

3) In the last scenario the wet slope parameter in the avalanche algorithm was changed. In section 3.3 and section 5.2.3 a relation was found between the run-up slope and the laboratory scale on which the experiment was applied. The calibration of the wet slope resulted in an improvement of the BSS from approx. 0 to 0.45 for small-scale experiments.

The validation of the model shows that the improvements obtained by the calibration iterations are similar for the other experiments. The simulated run-up is still too low; this can be explained by the fact that the run-up in XBeach is linked to the long waves.
Overall, it can be concluded that the calibration results in a better reproduction of the sediment transport and dune erosion for small-scale experiments. With the current model settings, the model performs well. To obtain better results with the XBeach-model, some formulations within XBeach probably need to be changed.

5.4 Conclusion

In this chapter the DUROS and the XBeach model were tested with the M1263 laboratory experiments. The series of experiments vary in the laboratory scales. The wave conditions and sediment properties were the same in all tests (reference conditions).

The model tests with the current DUROS model showed that the model performs very well for large-scale and very bad for small-scale experiments. The scale relations that are integrated in the model cannot be used to relate the profile on the different lab scales (chapter 3). As the model is calibrated with large-scale experiments, it is quite obvious that the model performs insufficient for small-scale (other) experiments.
In section 5.2.3 the current model was changed. Insights about the run-up zone from chapter 3 were used to introduce a run-up zone in the model. The run-up zone was put between the parabolic profile and the landward slope. The run-up zone in the model varies with other wave conditions and other foreshore slopes. The new DUROS model (research version) shows a consistent performance for all laboratory scales.

The XBeach model was also applied to all experiments. The default model settings were used from Van Thiel de Vries (2009). He calibrated the model with large-scale (Deltaflume scale=6) dune erosion experiments. The model showed an optimal performance for large-scale and insufficient performance for small-scale. Limiters and some empirical model parameters were found to cause some errors in the coastal profile in a small-scale simulation.
In section 5.3.3 three calibration steps have been discussed that resulted in a significant model improvement for small-scale experiments.
It is hypothesized that the improvement of both models for the series lab experiments on various scales goes with an improvement for prototype tests.

6 Model performance on prototype scale

6.1 Introduction

In this chapter, the DUROS and XBeach-model are compared at the prototype scale. It is assumed that when a model performs similarly at different laboratory scales, the model will perform comparable at prototype scale.
The DUROS predictions showed that the model performs pretty well for large-scale, but performs insufficient for small-scale experiments. The renewed model (DUROS research version) showed a consistent performance for all scale (BSS≈0.9). The simulations with the XBeach-model with default settings led to excellent performance at large-scale, but the model performs insufficient for small-scale experiments (n_d>5). The calibration of the model led to an improvement of the BSS from -0.20 to about 0.5 for small-scale experiments.
In order to evaluate the question, "*To what extent can the dune erosion models be used to simulate erosion on prototype scale?*" (**RQ-5**) the next two steps were carried out:

1) Extrapolate the model performance at different scales (see figure 6.1), i.e. assuming a trend in model performance for various scale, and extrapolating this performance to prototype.

2) Comparing both model performances on real storm surges. Until now, all experiments were conducted with the normative storm conditions (reference conditions). In this step the models are tested with less severe conditions.

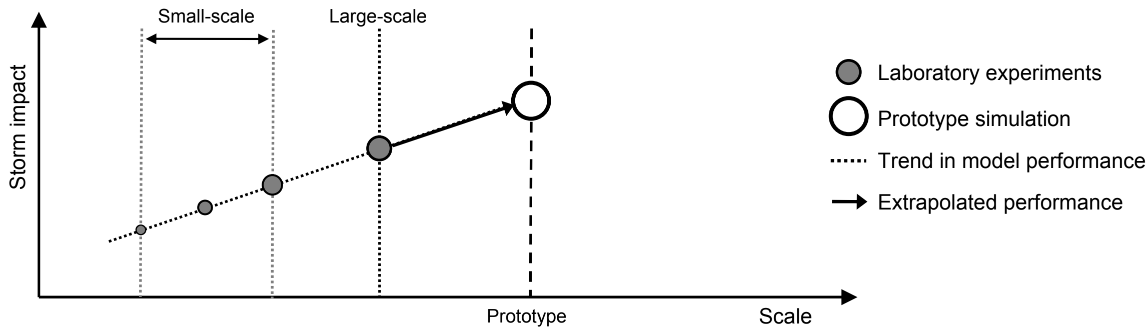


Figure 6.1: Research approach: Prototype (real/field scale) performance.

In section 6.2, the performances of both models are compared for the 'reference case'. For this purpose the current DUROS model (DUROS+) and the DUROS research version are used. Table 6.1 provides an overview of the XBeach settings (other from default). In section 6.3 the models are applied to the 1976-storm surge (DUROS+ and XBeach with adjusted settings).

Model parameter	Default (scale=6)	Prototype (scale=1)
hmin	0.2	1.2
eps	0.01	0.06
wetslp	0.1	0.067
hswitch	0.1	0.6
dzmax	0.003	0.0441

Table 6.1: XBeach parameter settings for prototype application.

6.2 Reference profile

The reference profile represents an average profile of the Dutch coast (see table 4.1). The hydrodynamic and morphodynamic conditions for the reference case are H_s=7.6m, SSL=5m, T_p=12s, D_{50}=225µm and storm duration t=45h (≈5h constant surge level). In figure 6.2, the predicted post-storm profiles with both models are shown (DUROS research version not included).

Comparing the DUROS+ model with XBeach (default and with adjusted parameter settings)

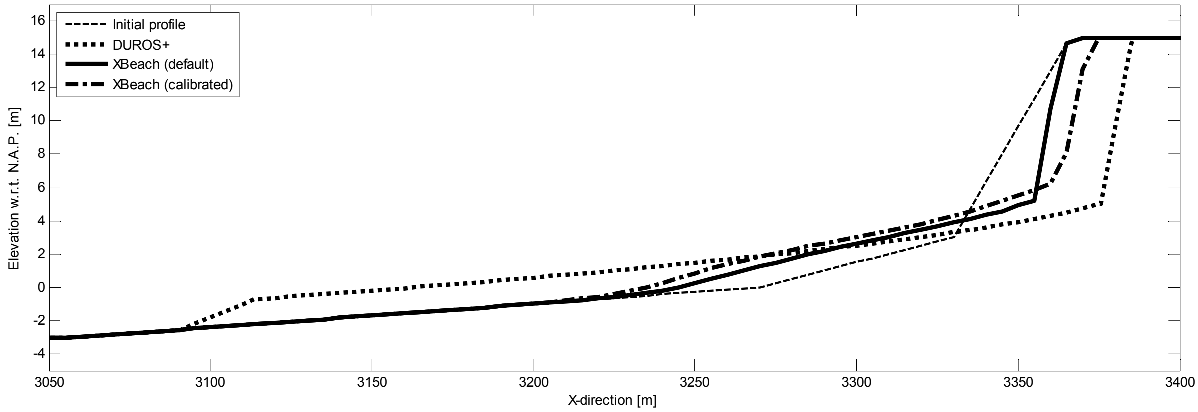


Figure 6.2: Prediction of the post-storm coastal profile on prototype scale (Reference Profile) with DUROS+ and XBeach.

The predicted post-storm profile with DUROS is twice the length as the simulated profile with XBeach. The combination of a longer and a gentler coastal profile led to larger dune retreat and more dune erosion. DUROS predicts almost four times more than XBeach with default settings (settings of scale experiment n_d=6). The changed parameters of the XBeach-model led to a broadening of the coastal profile for the prototype scale and a doubling of the erosion amount. The dune foot emerges above the surge level, which corresponds with the expectations (based on field observations).

Model	Version	Dune erosion [m^3/m]	Retreat at +12 N.A.P. [m]
DUROS	Plus (+)	294	26
DUROS	Research version	229	20
XBeach	Default (settings of scale=6)	86	5
XBeach	Adjusted settings	145	12
XBeach	*Van Thiel de Vries (2009)*	*170*	-

Table 6.2: Model results on prototype with reference conditions: Storm surge level=+5m N.A.P., T_p=12s, H_s=7.6m and D_{50}=225µm. The simulation of Van Thiel de Vries (2009) is somewhat larger because he only scaled the avalanche parameter dzmax, others were taken default.

Extrapolating model performance at different scales

The current DUROS model shows an inconsistent performance on various scales. Figure 5.4 and 5.5 show that the DUROS-model performs in terms of predicted erosion amount excellent (small overestimation) at large-scale and very poor (big underestimation) for small-scale. In section 4.2.2 and 5.2 it was argued that the DUROS-model cannot be used for small-scale experiments with prototype sediment, because erosion-dominant processes are different (figure 3.7 versus 3.8). The renewed model, in which the run-up zone was introduced, is capable of reproducing large-scale and small-scale experiments. The trend of consistent performance gives more confidence to the prototype prediction by the research model compared to the current DUROS model (DUROS+).

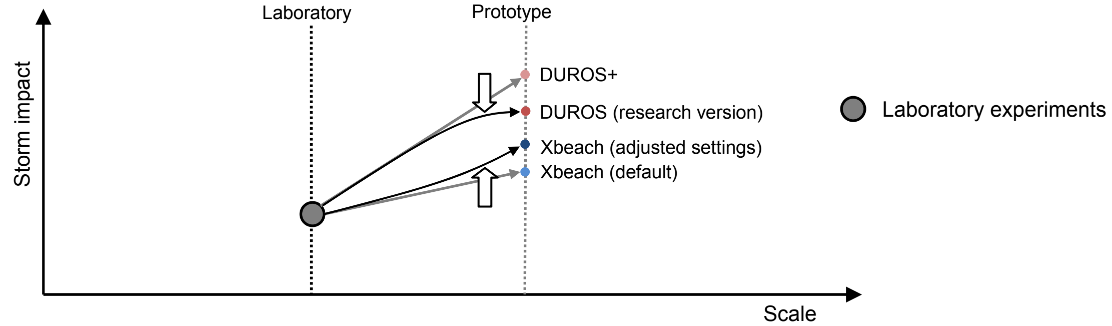


Figure 6.3: Storm impact on various scales: DUROS and XBeach predict similar storm impact on laboratory scale (gray circle) but deviate for prototype application (coloured circles).

Figure 5.17 shows that the (calibrated) XBeach-model performs reasonably well for all scales. This rather consistent performing on different scales gives more confidence for prototype application. In figure 6.3, the results for the current DUROS, renewed DUROS, default XBeach and XBeach with adjusted settings. Compared to the former results (DUROS+ and XBeach), the difference between predictions of the 'new' models becomes less (white arrows in figure 6.3).

6.3 Comparison of DUROS and XBeach with the '76 storm event

In the last decennium, two extreme storm events have occurred that led to large amounts of dune erosion: the '53 storm and the '76 storm. The first one, led to major flooding of the southern part of the Netherlands. The '53 storm event was the occasion for the development and construction of the Delta works. The storm also led to the start of the JARKUS (JAaRlijkse KUStmeting) project in 1963. Within this project, profile measurements were performed along the Dutch coast twice a year. In this section, the models are tested with the '76 storm. The '76 storm was chosen, because more detailed profile measurements are available. The models were applied to three transects of the Dutch coast: Julianadorp, Bergen aan Zee and Castricum (see bars in figure 6.5).

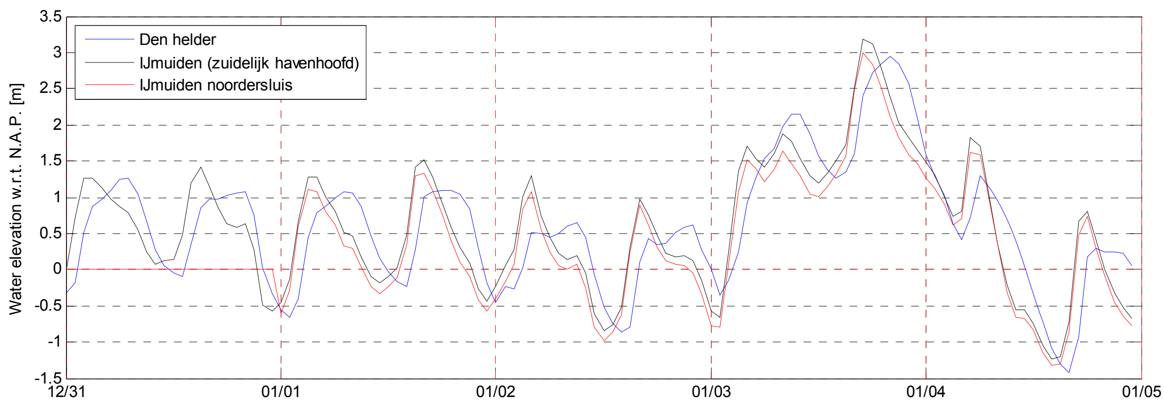


Figure 6.4: Measured water elevation: Measurements at Den Helder (blue line), Ijmuiden Noordersluis (black line) and Ijmuiden, zuidelijk havenhoofd (red line).

The storm event took place from 3 January in the morning until the 4th of January in the afternoon (see figure 6.4). For the model simulation, the interval [01/03/1976 00:00 – 01/04/1976 12:00] was chosen. A phase lag can be observed between IJmuiden and Den Helder that is caused by the counter clockwise propagation of the tide in the North Sea. The maximum storm surge for IJmuiden is slightly higher than for Den Helder.

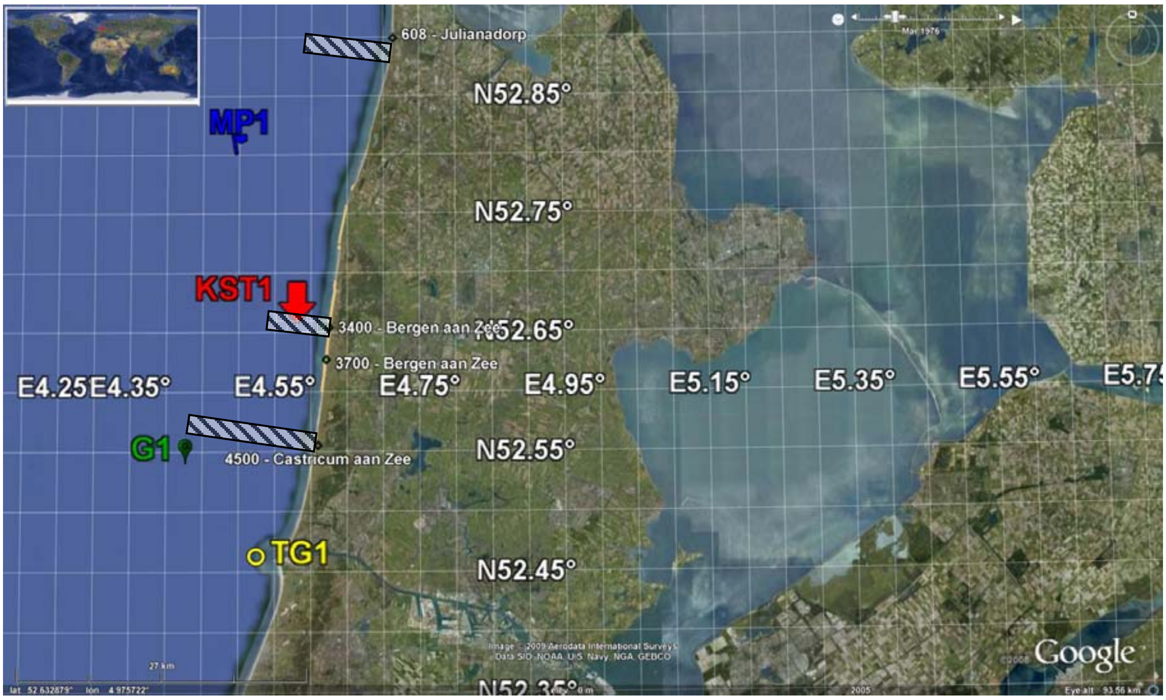


Figure 6.5: Chosen transects from the Dutch coast: Julianadorp (648), Bergen aan Zee (3400) and Castricum (4500). Buoys G1 and MP1 tracked the wave height (H_s) and (mean) wave period ($T_{m-1,0}$) during the storm surge.

Hydrodynamic (boundary) conditions

During the storm surge, the water levels were continuously monitored (see figure 6.4). Wave conditions were obtained with buoy MP1 (see figure 6.5). With a Delft3D-Flow simulation of the North Sea, offshore boundary conditions at 20m water depth (w.r.t. N.A.P.) were created (see appendix A-7). The simulated maximum storm surge level ($SSL_{s,max}$) is significantly smaller than the measured storm surge level ($SSL_{m,max}$) (WL| Delft Hydraulics, 1978). Also, the wave period and wave height were underestimated. So for representative storm simulation, only the measurements from buoy MP1 are used.

	Start of storm	End of storm	$SSL_{s,max}$ [m]	$SSL_{m,\ max}$ [m]	H_s [m]	T_p ($\approx 1.1T_{m-1,0}$) [m]
Julianadorp	01/03 00:00	01/04 12:00	*+2.20*	+3.03	6.27	11.50
Bergen aan Zee	01/03 00:00	01/04 12:00	*+2.25*	+3.18	6.27	11.50
Castricum	01/03 00:00	01/04 12:00	*+2.18*	+3.24	6.27	11.50

Table 6.3: Characteristics of the '76 storm surge for the three selected transects: Julianadorp, Bergen aan Zee and Castricum. The maximum significant wave height and the peak wave period were used from the buoy MP1 (Caires, 2008).

Model simulation of the '76-storm

The models DUROS+ and XBeach (with adjusted settings) are tested with these three prototype cases. For the hydrodynamic boundary conditions (H_s and T_p) the measurements from buoy MP1 are taken for all three transects. For the Julianadorp case, the surge measurements of Den Helder are used. For the other two cases the surge levels of IJmuiden are used.

The input sediment for all three locations are chosen to be the reference (D_{50}=225μm). In table 6.3, the results of both models are shown. The predicted post-storm profiles are shown in figure 6.6.

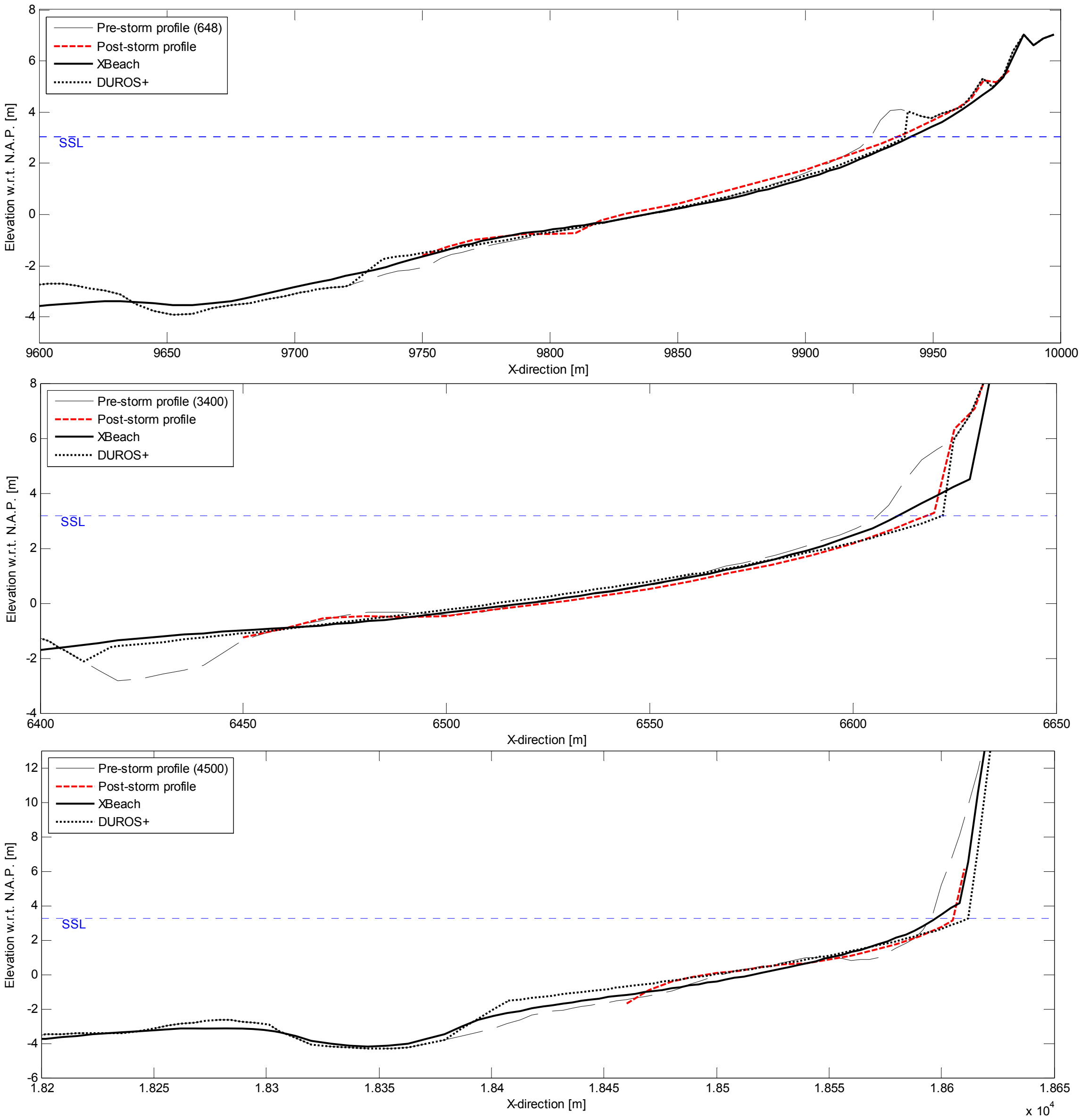


Figure 6.6: Model performance for three prototype cases. Dashed lines are the pre-storm profiles, dotted line is the DUROS+ prediction, solid line is the XBeach predicted and the red dashed line is the post-storm measurement. Upper panel: Case Julianadorp, transect 648. Middle panel: Case Bergen aan Zee, transect 3400. Lower panel: Castricum, transect 4500.

Location	Transect	Measured erosion E_m [m^3m^{-1}]	DUROS+ (measured B.C.)	XBeach (measured B.C.)
Julianadorp	648	**22.6**	23.9	46.2
Bergen aan Zee	3400	**48.9**	42.9	47.2
Castricum	4500	**55.0**	107.7	66.3

Table 6.4: Predicted erosion amounts above N.A.P. with DUROS+ and (calibrated) XBeach.

Comparing both model performance on real storm surges
The DUROS-model predicts the erosion amount at Julianadorp very well. For Bergen aan Zee the model slightly underestimates and it overestimates the erosion at Castricum with about 50%. In case of XBeach, the erosion at Julianadorp was overrated with about 50%. The erosion at Bergen aan Zee was slightly underrated and for Castricum the simulated erosion was 10m^3/m to large.

DUROS+ vs. XBeach
In chapter 4 it was found that for the reference case, DUROS predicts 40% more dune erosion than predicted with XBeach. However, table 6.4 indicates that DUROS and XBeach show rather similar erosion prediction for 'calm' storm conditions. The reason for this can be found in figures 4.6-4.7. The erosion amount for a surge level of approximately 3m above N.A.P. is relatively larger for XBeach (+) and the erosion amount for wave a wave height of appr. 6m is relatively larger for XBeach (+).

Where both models show to perform quite well for the case with measured BC's, the next things need to be considered:

- The DUROS model was designed for normative storm conditions; the '76 storm conditions are relatively 'calm' compared to the reference conditions (table 4.1). Especially the storm surge level (much lower) and storm duration differ for this storm event. As the model is not constructed for 'calmer' conditions the quite satisfying results seems just coincidence.
- The effect of wind on the hydrodynamics was not included; onshore directed wind (within the domain) cause an extra nearshore swell above the surge level. Also the presence of wind leads to different wave deformation in the nearshore zone.
- The sediment for all locations was assumed to be the reference; the measured erosion amount in Julianadorp is significantly smaller than in Bergen aan Zee and Castricum. A reason for this can be that the average sediment size in the Northern Dutch coast (Julianadorp) is larger. In both models, larger grains go with less dune erosion. (In XBeach this effect is minimal).
- Long-shore effects were not taken along; in the simulations only cross-shore sediment transport was assumed. The simulations are therefore only true-to-nature, if the long-shore sediment transport flux is negligible.
- The storm impact was assumed to be taken place from January 3th 0:00 until January 4th noon; It was assumed that during the 'calm' conditions before and after the selected period no dune erosion processes occurred.

6.4 DUROS versus XBeach

The DUROS and the XBeach model are based on the same series of laboratory experiments. These laboratory experiments differ in lab scale but correspond in hydrodynamic conditions (reference conditions). Despite that the models are based on similar lab experiments, some differences between the models have been found. In this section, the differences and similarities are discussed. Table 6.5 provides the overview. The models correspond in the experiments they are based on (calibrated with), but differ in the way these experimental results are 'translated' to prototype scale. The DUROS model is created for storm surge duration of ~45 hours. This normative storm (North Sea storm surge hydrograph=surge effect + tidal effect) was simplified by a storm with a constant water level of 5 hours. The XBeach model proved to be capable of simulating storm surge similar, longer and shorter than this normative storm.
In this study the DUROS and XBeach model were tested for 1D cross-shore models. XBeach is also capable of simulating longshore erosion processes.
As both models are based on experiments with normative conditions, less and more extreme conditions were not tested. A model sensitivity analysis (see chapter 4) discovered that the models shows much similarity in sensitivity to other storm conditions (for detailed comparison see

table 4.4). In case of DUROS, a very important limitation is that the pre-storm profile does not affect the post-storm profile shape. E.g. in cases of very shallow or very steep foreshore, the waves dissipate differently, resulting in another post-storm profile (with the same boundary conditions). In XBeach this effect is taken along.

		DUROS+	XBeach
Background		Based on distortion relation of Vellinga (1986) and results of distorted scale experiments	Modelling of nearshore processes separately, combining those leads to sediment transport. Calibrated with distorted scale experiments
Erosion prediction		General post-storm profile fixed at storm surge level	Time-interval adjusting of the profile due to sediment transport rates
Application	Temporal	Fixed storm duration and intensity. (North Sea hydrograph of 45h)	(Un-) limited (~5 days)
	Spatial	1D cross-shore	2DH (cross- and longshore)
Limitation		Model is based on reference case conditions (see table 4.1). Post-storm profile is independent of pre-storm profile	Model is based on reference conditions ('extreme' erosion processes)
Sensitivity		Scale relations	Processes
		See table 4.4	

Table 6.5: Comparing DUROS and XBeach model.

6.5 Conclusion

In this chapter, the models were compared for the reference case and for a real storm surge. In the first case, the model performances on various laboratory scales were extrapolated to prototype (by means of a trend). In case of the current DUROS, it was argued that the model can only be applied to experiments in which the erosion-dominant processes are similar with the processes of the experiments the model was constructed with (large-scale). In chapter 3 it was found that this is not the case for the small-scale experiments from the M1263 program. Therefore, a trend in model performance (figure 5.4) cannot be extrapolated to prototype. In case of the DUROS research version, the model performs very constant for all scales. This gave more confidence to the prototype prediction. The DUROS research version predicts 20% less dune erosion than the current DUROS model (230 compared to 290 for the current model).
In case of XBeach, several numerical parameter settings were adjusted. The changes led to consistent model performance for various laboratory scales (BSS≥0.5). The changes led to about 50% more erosion amount on prototype compared to the default simulation. Compared to the simulations of Van Thiel de Vries (2009), the predicted erosion amount with XBeach with adjusted settings is 15% less (see table 6.2).

In section 6.3, the models were tested with a real storm surge; the '76 storm surge. Three locations, Julianadorp, Bergen aan Zee and Castricum, were chosen for which measurements from buoys were taken for the hydrodynamic conditions. The DUROS-model shows to perform quite well for transect Julianadorp and Bergen aan Zee and overestimates for Castricum tremendously. XBeach overestimates the erosion at Julianadorp with almost 50%. For the other two cases the model performs very well.
The similarity in performance (in terms of dune erosion volume) for the two models can be explained by the fact that XBeach is less sensitive to smaller storm surge levels and less sensitive to smaller wave heights, compared to DUROS. So, compared to the reference case, for less severe storm surges (they are <u>not</u> designed for) the model predictions become more similar.

7 Conclusion and recommendations

7.1 Conclusion

Objective and research question

The objective of this study was to get a better understanding (feeling) of the underlying causes for differences in dune erosion predictions. For this purpose two research questions were formulated: *What causes the difference in storm impact predicted by DUROS and XBeach for reference conditions?* And *what consequences do these differences in storm impact have on the prediction for prototype scale?* The DUROS+ and XBeach showed very good performance for large-scale experiments. When applying to small-scale experiments, both DUROS and XBeach perform insufficient. In case of DUROS, the run-up zone was not integrated well. XBeach simulations show the similar problem and above that, lacks in continuity of the post-storm profile. Limiters in the model were found to cause this discontinuity. After implementing a run-up zone for DUROS (DUROS research version) and adjusting (scale dependent) model parameters for XBeach, both models show significant performance improvement for the small-scale experiments.
The two revised models showed better performance for all experiments. For the prototype prediction this changes lead to less dune erosion for DUROS and more dune erosion for XBeach (compared to the former models). The difference of the revised models is now 30% (earlier 40%).

The research questions were evaluated in 5 chapters in which, erosion processes, scaling rules, the model characteristics, model sensitivities and model performances on laboratory and prototype scale were investigated.

Modelling of dune erosion

For the aid of understanding the quantity of dune erosion that goes with normative hydrodynamic conditions, several laboratory experiments were performed. The advantage of lab models is that desirable conditions can be created and erosion processes can continuously be monitored. Laboratory experiments on various scales with similar sediment property were examined. The coastal response for experiments on the same scale showed much similarity; the horizontal variance between the post-storm profiles is relative small compared to the horizontal change in relation to the initial (pre-storm) profile. The transport rates showed to be strongly dependent on the scale; large-scale transport rates are much higher than small-scale transport rates. Also, the wave run-up, that is dominant for erosion rates on small-scale, showed to be strongly dependent on the scale. It was found that the run-up heights in scale (read: distorted) experiments is about $n_d^{0.56}$ too high (see section 3.4).

Scale relations were created to relate dune erosion amounts in laboratory with actual dune erosion in the field (prototype). The distortion relation of Van de Graaff (1977) and Vellinga (1978) was obtained when relating erosion amounts on different lab scales. The distortion rate (n_d/n_l) is a function of the lab scale (n_d) and the sediment fall velocity (n_{ws}). In chapter 3, it was found that the relation is not capable relating transport processes in lab experiments on various scales with similar sediment properties. The distortion relation was integrated in the dune erosion prediction model (DUROS) together with an average coastal profile (extrapolated from lab results).

Erosion prediction

The DUROS-model was integrated in the Dutch guidelines, for modelling the storm impact (dune erosion and dune retreat) on prototype. The model has an empirical approach, i.e. relations gathered in the lab were directly linked to hydrodynamic parameters on prototype. The DUROS-model was compared with the process-based XBeach-model. This model computes hydrodynamic and morphodynamic processes separately to predict actual dune erosion.

The sensitivity of both models to changing hydrodynamic (surge level (SSL), wave height (H_s) and wave period (T_p)) and morphodynamic (grain size (D_{50}) and shape of coastal profile) conditions was analysed. The predicted erosion amount for the reference case with DUROS is approximately 40% higher than with XBeach. The DUROS-model is more sensitive for the surge level than XBeach. The erosion amount predicted with DUROS even drops below the XBeach predicted for SSL<4m. The models are similar related to the wave height. In case of DUROS, the prediction seems to be inadequate for wave height above 10m. For the wave period, a range of 10s to 22s was investigated. The XBeach-model seems to be more sensitive for longer wave periods. The erosion prediction with XBeach exceeds that of DUROS for T_p>20s.

Parameter	DUROS	XBeach	DUROS vs. XBeach
Surge level	++	+	>
Wave height	+	+	=
Wave period	+	++	<
Sediment size	++	+/-	>
Horizontal stretch	--	-	>

Table 7.1: Model sensitivity: Model predictions are positive (+) or negative (-) related to the parameters. In case that model A is strongly dependent on a parameter (++) and model B not or less, model A has a higher dependency than model B (A>B). In case that model A & model B are similar related to a parameter, their dependency is similar (=).

DUROS seems to be very sensitive to other sediment sizes. A 30% decrease in grain size results in about 60% more dune erosion. The XBeach-model shows quite similar simulations for varying sediment sizes. A broader coastal profile results in a decrease of erosion volume for both models. The DUROS-model shows much more sensitivity.

Comparing lab results with model predictions

As both models were based on the results of lab experiments, they were expected to perform quite good when verifying with the experiments. The verification of DUROS showed that the model performs very well for large-scale experiment, but insufficient for small-scale experiments (underestimation of the erosion amount). The scale dependency of the transport rate and the wave run-up was hypothesised to be the cause for the insufficient performing.
The run-up zone that was studied intensively in chapter 3 was implemented in the DUROS model, resulting in the DUROS research version. The changes in the model led to good performance of the model for all scales.

When comparing XBeach simulation with the lab experiments, it was found that the model performs excellent for the large-scale experiments, but perform insufficient for small-scale. In small-scale the simulated profile development strongly diverts from the observed (measured) profile development. It was suggested that some parameter settings in the model needs to be adjusted when applying the XBeach-model on various scales.
In section 5.3.3, six parameters were introduced that needs to be changed for different scales: Three parameters of the avalanche model, a cut-off water depth for the Stokes drift included return flow, a cut-off water depth for sediment transport and the near-bed turbulence. The scaling of the first five parameters was performed according to their unit. It was hypothesised that the near-bed turbulence was overrated for small-scale experiments. Therefore, this contribution was excluded from the total flow velocity that induces sediment transport. The verification of the XBeach-model

with adjusted parameter settings showed that the model performance increased significantly for small-scale experiments (BSS≈0.5). A better performance (BSS≥0.8) was obtained when changing the transport formulation in the model (to relation (5.10)). The validation of the model showed that the proposed scaling of five parameters is valid. Therefore, it was assumed that the scaling can also be used for prototype parameter settings.

Comparison on prototype
Both models perform excellent for large-scale experiments. The discrepancy between the models for the prototype reference case implies that the lab-prototype conversion in both model approaches is different. In case of DUROS, a prototype profile was obtained by a logarithmic extrapolation of lab profile, and calibrated by means of volumes with large-scale experiments and the distortion relation. Thus, according to DUROS, the erosion process in large-scale experiments is less intense in relation to erosion processes on prototype. This is in line with the expectations. In chapter 3, it was found that the wave run-up has a large contribution to the actual dune erosion. Since this effect becomes less important for larger scales (according to relation(3.12)), it was assumed that DUROS is calibrated with too high (laboratory) erosion rates. The DUROS research version that takes this run-up effect along, predict less dune erosion on prototype.
In case of XBeach, some parameter settings were adjusted. The changes led to consistent model performance for various laboratory scales. The changes led to about 50% more erosion amount on prototype (compared to XBeach with default settings). The difference between the revised models becomes less compared to the former models. The XBeach model with adjusted settings predicts 30% less dune erosion than the DUROS research version (earlier 40%).

The models were also tested with a real storm surge; the ’76 storm surge. Three locations, Julianadorp, Bergen aan Zee and Castricum, were chosen for which measurements from buoys were taken for the hydrodynamic conditions. The DUROS+-model shows to perform quite well for transect Julianadorp and Bergen aan Zee and overestimates for Castricum tremendously. XBeach overestimates the erosion at Julianadorp with almost 50%. For the other two cases the model performs very well.

With the performance results on various scales and results for three real storm surges, can be concluded that the XBeach-model in relation to DUROS research version;

- 1) is <u>similar</u> applicable for simulation erosion processes on various scales (chapter 5),
- 2) is <u>similar</u> applicable for simulation erosion processes on prototype scale (chapter 6).

For practical purposes, the DUROS-model seems to be much easier to conduct. The model prediction shows to be at the ‘safe side’ for the three investigated transects. But, when the test-case deviates too strongly from the reference case, the erosion-dominant processes are expected to deviate in such way that they are not in proportion anymore with the erosion-dominant processes, the DUROS-model was based on. In that case, it is recommended to perform the safety assessment with an advanced tool like XBeach.

7.2 Recommendations

Dune erosion experiments

- In this research a series of laboratory experiments were examined. These experiments differ in the lab scale in which they were conducted. Due to limiting dimensions of the test facilities the scale experiments got a certain model distortion: length and depth ratio is not in proportion with the reference case. It was found that this model distortion leads to too higher run-up levels. Consequently, this relatively high run-up led to more dune erosion.

To preclude this effect, it is recommended to conduct future lab experiments with undistorted models.

- When comparing the reference conditions (table 4.1) with the normative storm conditions prescribed in the current guidelines for safety assessment (HR2006), it was found that the reference conditions are less extreme. It is recommended to change the reference case conditions to be conducted in future lab experiments.

Scale relations

- The scaling relation (or distortion relation) was deduced by relating erosion amounts on different laboratory scales. In this work most effort was spend on finding the optimal distortion factor α. The morphological timescale was investigated insufficiently (in the author's opinion). The lack of measurements on a number of time series, the validity of this timescale couldn't be checked. For further research with scaling rules (DUROS) it was recommended to verify this.
- The DUROS-model is based on the distortion relation by; 1) the sensitivity is implicit related and 2) the model calibration was performed with the distortion relation. In this study, the model was tested with small- and large scale experiments. For this application, the lab tests had to be converted to prototype first before modelling. Afterwards, the model results had to be converted (back) to lab, in order to compare them with the measurements. In this study, this conversion was performed with the distortion relations (spatial and temporal). It is also possible to choose other distortion relations.

XBeach model

- In chapter 3, it was found that the erosion rates in small-scale was strongly related to the wave run-up height. In XBeach, only the run-up of long wave is taken along. As short waves also contribute to the run-up and consequently, the part of the dune that gets instable and avalanches, it was recommended to further study this effect and probably introduce this in XBeach.
- In chapter 5, five parameters were introduced that were expected to be scale dependent. The good results of the validation with all lab experiment gave more confidence to the validity of the choice for these parameters and the proposed scaling. The prototype runs showed also good results. It was also expected that the minimal fall velocity parameter *Tsmin* in the model, becomes more important when applying it for smaller scale experiments. During the model-calibration the near-bed turbulence was also changed. It was expected that the model overrates this effect for small-scale. Therefore, this factor was excluded for small-scale. Currently, this effect can only be changed by turning it off. It was recommended to further investigate the scale dependency of these parameters.

Modelling dune erosion with XBeach

- The XBeach-model was calibrated on Deltaflume scale. This study showed that it can also be applied on smaller <u>and</u> larger scales. For the application on various scales it is essential to choose the correct magnitude of the scale dependent parameters in the model. As the XBeach manual currently provides insufficient knowledge about this scale dependency, hence it was recommended to add this to the manual to maintain uniform model-usage.

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Notions, abbreviations and symbols

ROMAN symbols:

Symbol	Unit	Meaning
A		Avalanche parameter (s)
A_0	m^3m^{-1}	Dune erosion quantity
A_{sb}	-	Bed load coefficient
A_{ss}	-	Suspended load coefficient
BSS	-	Brier Skill Score
C	m^3m^{-3}	Depth-averaged sediment concentration
c	m^3m^{-3}	Sediment concentration
C_{eq}	m^3m^{-3}	Equilibrium sediment concentration
D	m	Water depth
D_{50}	µm	Median diameter of sediment grains by mass
D_{90}	µm	Sediment diameter for which 90% by weight is finer
d_m	-	Parameter value on laboratory
d_p	-	Parameter value on prototype
dryslp	-	Critical dry slope for avalanching
dzmax	ms^{-1}	Maximum erosion speed during avalanching
E	J	Wave energy
F	Hz	Frequency
F	s^{-1}	Coriolis coefficient
f_{mor}	-	Morphological acceleration factor (1-10)
f_p	s	Peak frequency
Fr	-	Froude number
g	ms^{-2}	Gravitational acceleration
h	m	Water depth
H	m	Wave height
H_0	m	Deep water wave height
H_{0s}	m	Significant wave height (average of one-third highest waves)
H_{m0}	m	Wave height (in XBeach)
H_{rms}	m	Root mean square wave height
H_{sig_t}	m	Wave height (in DUROS)
hswitch	m	Water depth at wet-slope/dry-slope interface
k_b	$m^2\ s^{-2}$	Bore-averaged near-bed turbulence energy
L	m	Characteristic length (or wave length)
m_{cr}	-	Critical slope (different for wet and dry)
n_A	-	Erosion volume scale parameter
n_d	-	Depth scale parameter (=n_h)
n_{D50}	-	Grain size scale parameter
n_h	-	Height scale parameter (=depth scale parameter for undistorted models)
n_H	-	Wave height scale parameter
n_L	-	Horizontal length scale parameter
n_{s-1}	-	Relative density scale parameter
n_T	-	Wave period scale parameter
n_t	-	Time scale parameter
n_{Tm}	-	Morphological time scale parameter
n_u	-	Velocity scale parameter

Symbol	Unit	Meaning
n_v	-	Velocity scale parameter
n_{ws}	-	Fall velocity scale parameter
n_x	-	Charateristic length scale parameter
n_ϕ	-	Slope scale parameter
p	-	Porosity of the bed
Pb	-	Probability of wave breaking
q_{ret}	m^2s^{-1}	Flow rate of sediment in a vertical plane
r	-	correlation coefficient
Re	-	Reynold number
$R_{u2\%}$	m	Run-up height (computed)
R_{um}	m	Measured run-up height in laboratory
Rv	m	Run-up height (by Battjes)
S_f	-	Scale factor
SSL	m	Storm surge level
ss_{xx}	-	Sum of the squares values
ss_{xy}	-	Sum of the squares residuals
ss_{yy}	-	Sum of the squares values
St_f	-	Steepness factor
S_x	$kgm^{-1}\ s^{-1}$	Sediment transport per unit width
t	s	Time
t_{eq}	s	(quasi-) equilibrium state
T_p	s	Peak wave period
T_{p_t}	s	Wave period (in DUROS)
T_s	s	Adoption time of sediment
u_{cr}	ms^{-1}	Depth-averaged critical flow velocity
u_{crm}	ms^{-1}	Depth-averaged critical flow velocity for motion
u_{crs}	ms^{-1}	Depth-averaged critical flow velocity for suspension
U^E	ms^{-1}	Flow velocity in x-direction (Eulerian)
u_g	ms^{-1}	Horizontal velocity of grains
u_{rms}	ms^{-1}	Orbital flow velocity
V	ms^{-1}	Characteristic velocity
wetslp	-	Critical wet slope for avalanching
WL_t	m	Storm surge level (in DUROS)
w_s	ms^{-1}	Settling (fall) velocity sediment grains
X_i	-	Data point
z_b	m	Bottom profile
z_{b0}	m	Initial coast profile
z_{bc}	m	Predicted coast profile
z_{bm}	m	Measured coast profile
z_{s0}	m	Still water level
zs0	m	Storm surge level (in XBeach)

GREEK symbols:

Symbol	Unit	Meaning
α	-	Exponent applied to describe the distortion of a model
β	-	exponent to describe the time scale relation
δ	m	Measurement error
η	m	Water level
η_1	m	Wave through level
θ	^{o}	Angle of incidence
ρ_s	kgm^{-3}	Mass density of sediments
ρ_w	kgm^{-3}	Mass density of fluids
$\phi_{foreshore}$	-	Foreshore slope (-3 till +3 N.A.P.)
$\phi_{run\text{-}up}$	-	Run-up slope

A Appendices

A.1 DUROS

A.1.1 DUROS(+) Deduction

The purpose of the research Vellinga executed from approximately 1980 until 1985 was to improve the provisional model of van de Graaff (1977) that was mainly based on field observations of the 1953 storm surge. This was achieved within the research program M1263 in which large amount of small-scale and large-scale experiments were done.

During the research program, Vellinga found the next results from laboratory and field investigation to develop a new dune erosion model:

1) A typical erosion profile will develop during a storm surge with dun erosion. The shape of the profile is <u>independent</u> of the initial profile. However, it is strongly dependent on the grain size. The seaward extent of the profile is determined by wave height and grain size.

2) A fully developed equilibrium profile will not be attained during a typical North Sea storm surge. The shape of the profile remains rather constant but the extent increases with time.

3) The model tests demonstrate that during the storm surge a typical erosion profile develops which extends to a water depth of about $0.75H_{0s}$ below storm surge level.

4) Three-dimensional model tests with movable bed and random waves indicate that, given the wave height just outside the breaker zone, the angle of the wave incidence has <u>no</u> significant effect on the erosion quantity.

5) The set-up of the model tests (different lab scales) allows for the development of scale relations regarding length, depth and grain size. By means of these scale relations the erosion profile can be described in terms of wave height H_{0s} and fall velocity w_s.

6) A number of 58 field measurements of the 1976 storm have been analyzed and the provisional prediction model had been evaluated, what concludes to:

- The provisional model overestimates the erosion quantity by a factor 1.5 to 2.0 for average coastal profiles, and by a factor 2 to 10 for steep profiles.
- Examination of the 58 erosion profiles clearly shows a relation between grain size and profile steepness.

In the next paragraphs the deduction to the current DUROS model will be discussed. Figure A-1.1 provides an overview of the steps that were undertaken to come to the model.

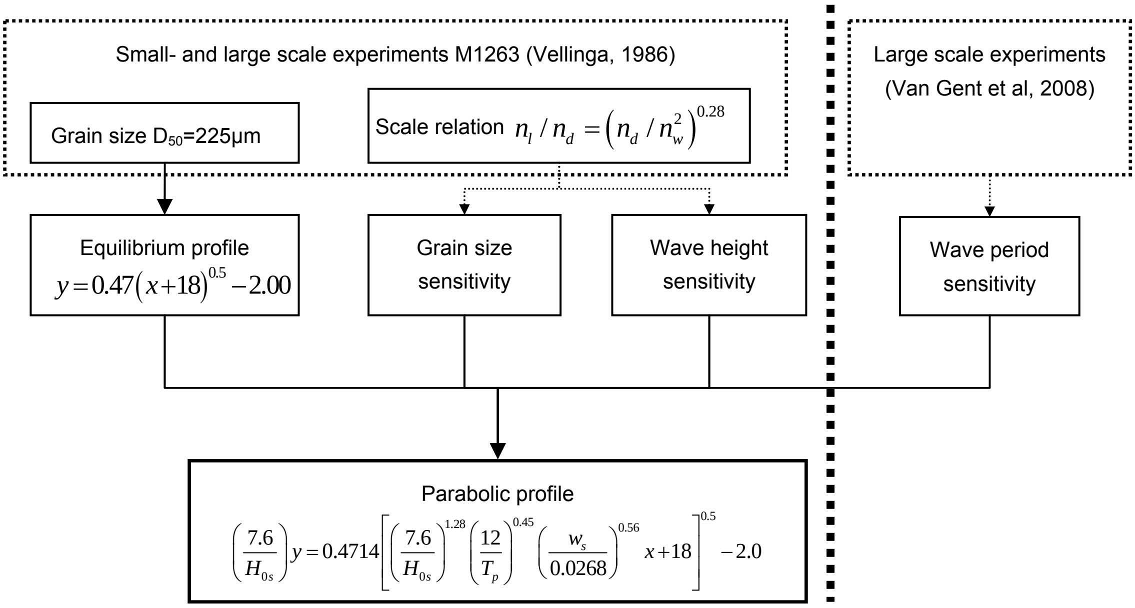


Figure A-1.1. Scheme for DUROS deduction. The fat dotted line divides the DUROS version of Vellinga (1986) on the left and the additional wave period influence, added in 2008 by van Gent et al., on the right.

<u>Equilibrium profile from laboratory results</u>

The erosion profiles measured in the laboratory experiments were converted to prototype with the scale relations. The agreement is not fully satisfactory, as a distinct scale effect can be observed in the reproduction of the run up zone (above storm surge level). Since this scale effect is not described by the scale relations, a direct extrapolation of model profiles was carried out to determine the erosion profile for prototype (see figure A-1.3). To avoid uncertainties with regard to the effect of the grain size only the tests with grain size 225μm were considered (see table A-1.1).

	Lab scale (n_d)			
Grain size	5	26	47	84
225 μm	III-test I III-test II	II-test 121 II-test 125	II-test 101 II-test 105	II-test 111 II-test 115

Table A-1.1. Laboratory experiments M1263 (II & III) that are used to construct DUROS' prototype profile.

First the position of the dune foot was determined; next the erosion profile was derived, as a best fit of model profiles. On the basis of a careful analysis of model and field data, the position of the dune foot to be applied in the dune erosion prediction model has been fixed at storm surge level.
To determine the erosion profile, the averaged [per depth scale (n_d)] model profiles have been converted to prototype with the Froude relation (n_d=n_l) (see figure A-1.2).

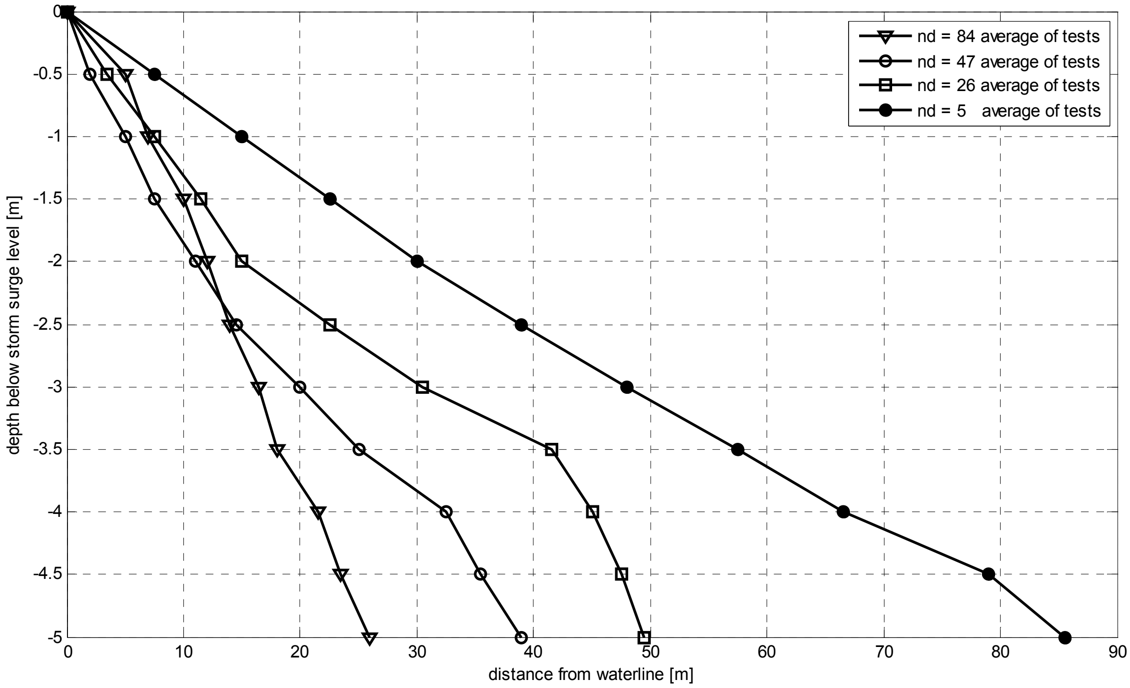


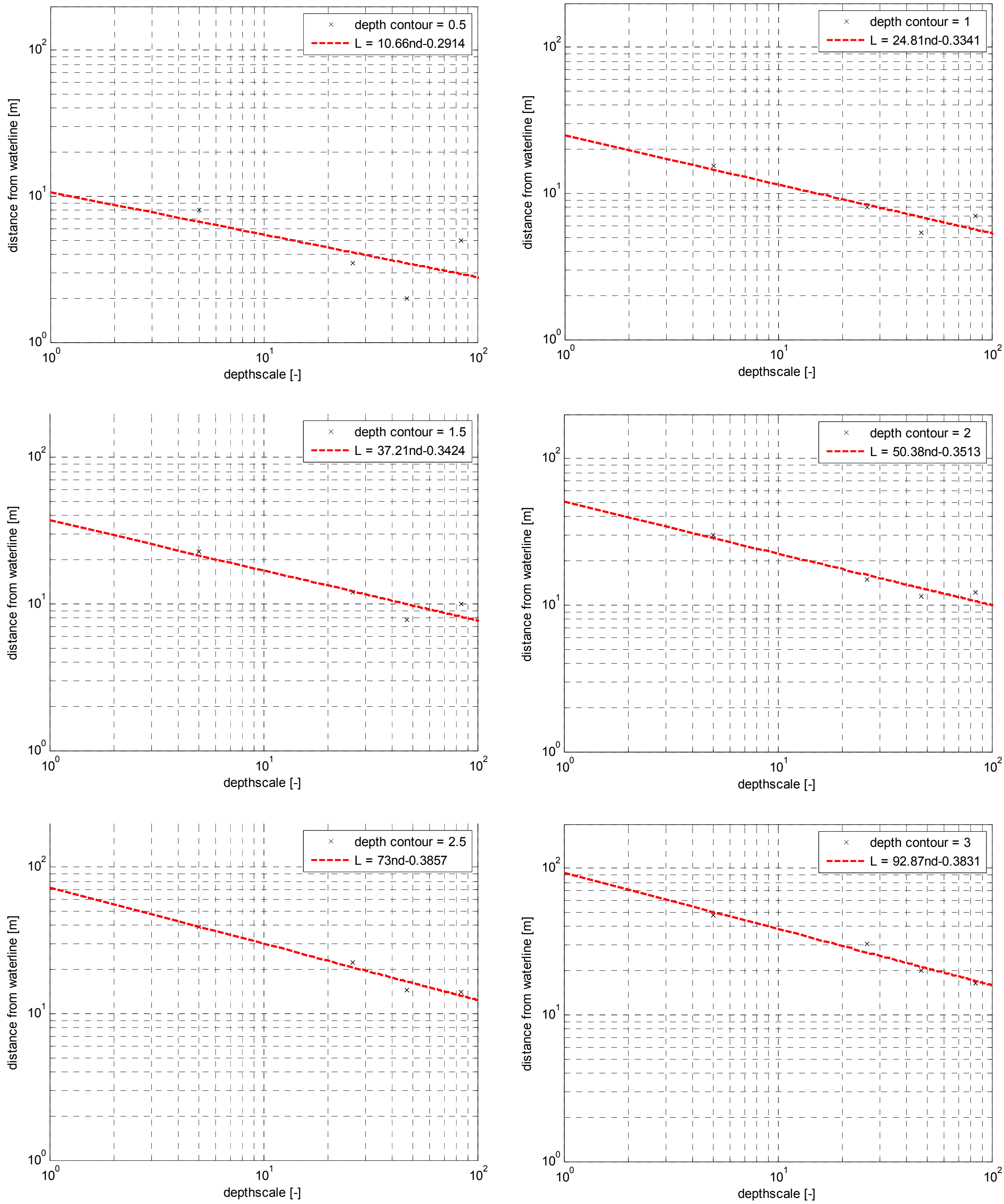
Figure A-1.2: Geometrically scaled tests to prototype with grain size=225μm.

A distinct scale effect can now be observed as the distorting relation, in which the steepness of the profile is a function of the depth scale factor, has not been applied.

The erosion profile for the 1:1 situation has been determined by extrapolation of the horizontal distance L between the waterline and the depth contours gathered with lab simulations. The extrapolation has been carried out along the ‘best fit’ line:

$$L = \beta * n_d^{\alpha} \quad \text{(A 1.1)}$$

The values for β and α* have been determined by curve-fitting (figure A-1.3), see also table A-1.2. The result of the extrapolation for various depth contours is shown in figure A-1.4.


depth contour = 0.5
L = 10.66nd-0.2914
depth contour = 1
L = 24.81nd-0.3341
depth contour = 1.5
L = 37.21nd-0.3424
depth contour = 2
L = 50.38nd-0.3513
depth contour = 2.5
L = 73nd-0.3857
depth contour = 3
L = 92.87nd-0.3831
distance from waterline [m]
depthscale [-]
10^0
10^1
10^2

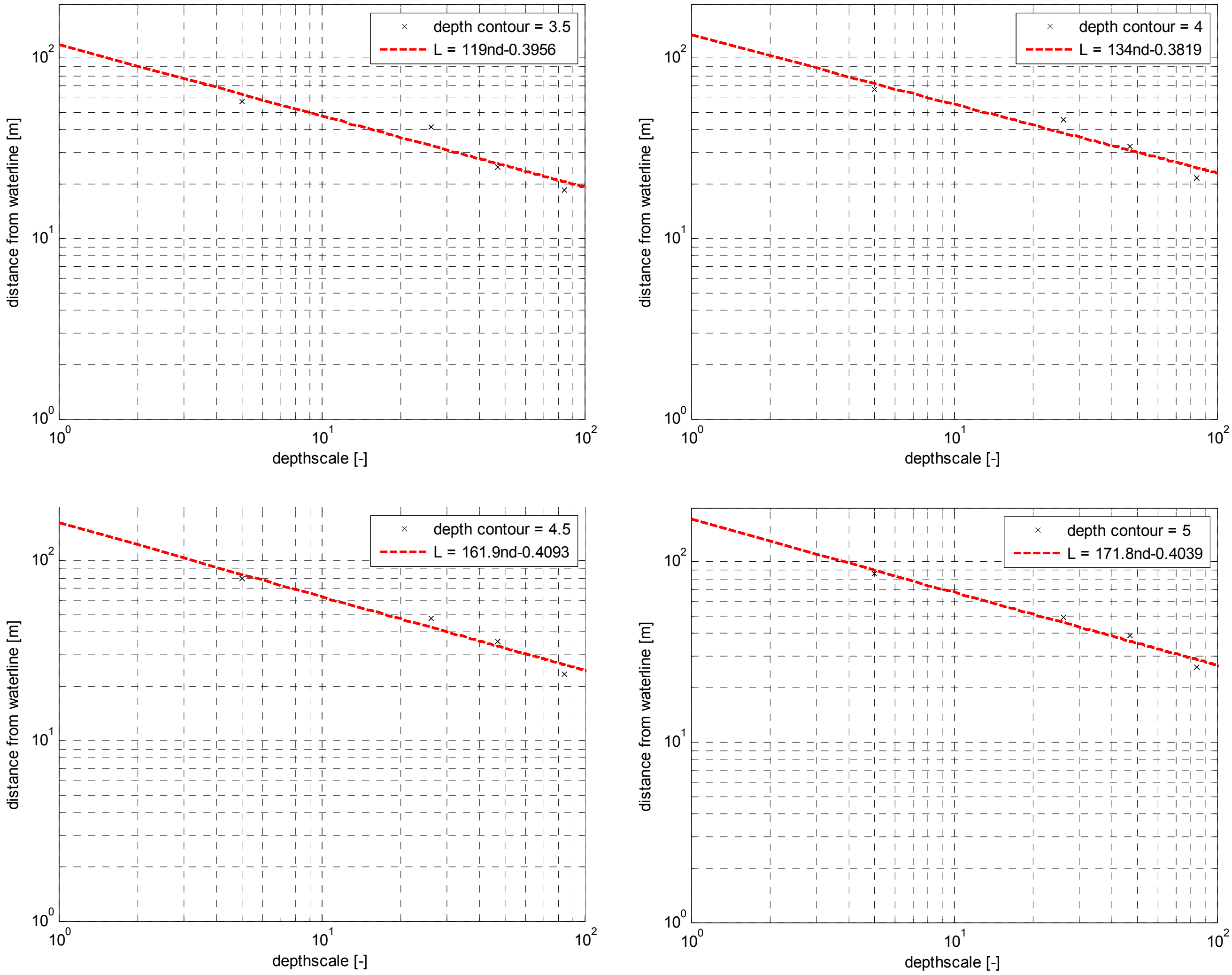


Figure A-1.3: Horizontal distance L for all scales on depth contours [0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0] m. Intersect of the fitted line (red dashed) and the y-axis represents the horizontal distance on prototype.

	This study (log-fit)		Vellinga (1982)		This study (lin-fit)	
Depth contour [m]	β [m]	α* [-]	β [m]	α* [-]	β [m]	α* [-]
0	-	-	-	-	-	-
0,5	11	-0,291	12	-0.33	14	-0.352
1,0	25	-0,334	24	-0.32	28	-0.368
1,5	37	-0,342	37	-0.34	41	-0.372
2,0	50	-0,351	52	-0.36	55	-0.382
2,5	73	-0,386	73	-0.38	72	-0.382
3,0	93	-0,383	94	-0.38	86	-0.357
3,5	119	-0,396	119	-0.39	102	-0.339
4,0	134	-0,381	134	-0.38	117	-0.334
4,5	162	-0,409	163	-0.41	145	-0.371
5,0	172	-0,404	177	-0.41	158	-0.374

Table A-1.2: Values for α and β determined by different curve-fitting approaches.

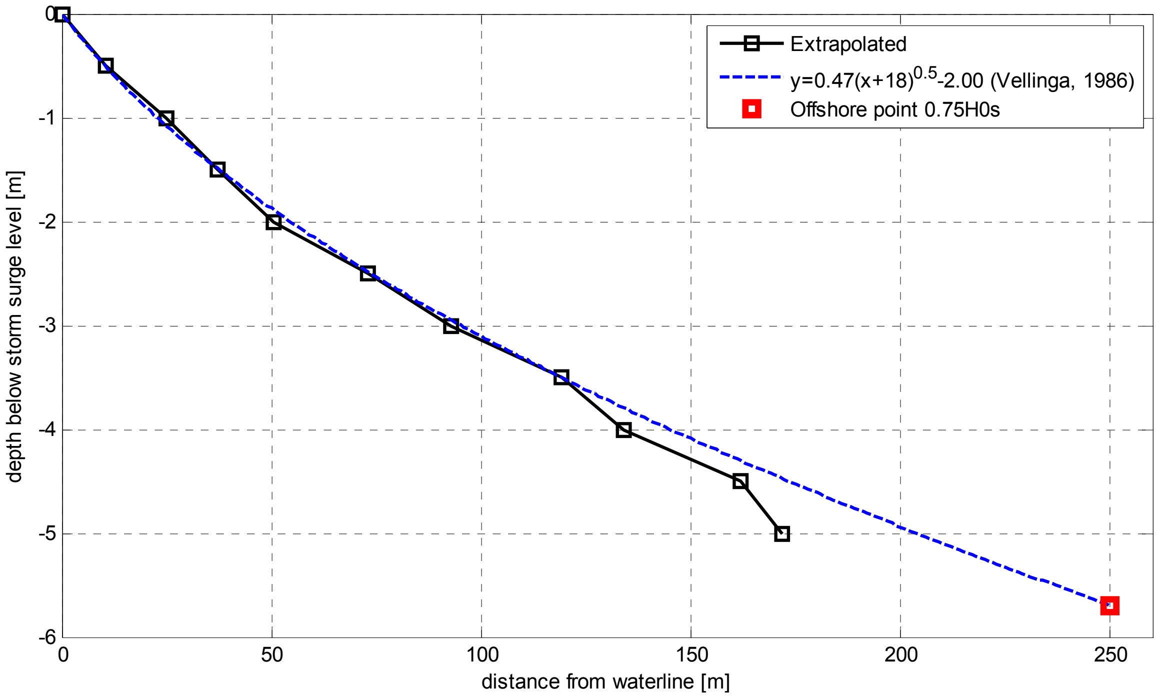


Figure A-1.4: Prototype erosion profile via extrapolation by Vellinga (1986).

*Note: the (average) values for α used to extrapolate the laboratory profile to a general prototype equilibrium profile are not in accordance with the earlier evaluated α-value in the scaling rules.

A regression analysis for the points from the waterline down to the 3.5m depth contour and the offshore point $0.75H_{0s}$, leads to the following expression for the extrapolated profile:

$$y = 0.47\left(x+18\right)^{0.5} - 2.00 \quad \text{(Vellinga, 1986)} \qquad \text{(A 1.2)}$$

In which the dune foot is fixed at x=0 and y=0. This profile is valid for storm surge conditions with H_{0s}=7.6m, T_{rep}=12s and D_{50}=225μm, for t=5h with a constant storm surge level (Vellinga, 1986).

Land and seaward extent of the parabolic profile

Seaward side～recovery distant

The shape of the erosion profile, its extent in seaward direction and the recovery distance of the amount of eroded sand are directly related. A determination of the seaward extent of the erosion profile by extrapolation of the measured erosion profile is rather inaccurate due to minor scale effects and random variations in the position and shape of the most seaward part of the erosion profile. The sediment balance is defined to be more accurate and is therefore used. The exact distance to be introduced in the prediction model has been determined by calibrating the model to specific laboratory experiments. By 'trial and error' an optimal distance for the seaward extent is gathered, see table A-1.3. A depth of 5.72m below SSL is found, that is equal to $0.75H_{0s}$ and a distance of 250m from the dune foot. The downward slope on the seaward end is fixed at 1:12.5, based on a careful analysis and interpretation of small-scale and large-scale model data.

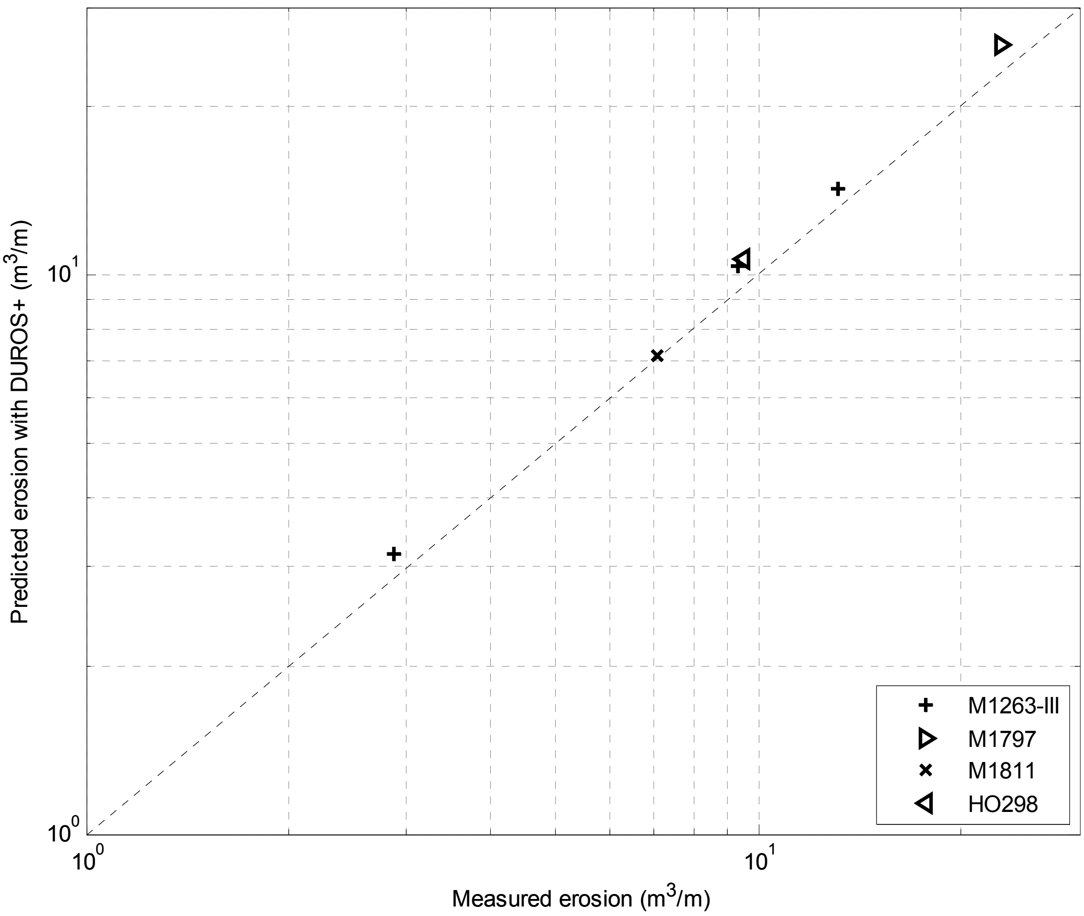


Figure A-1.5: Result of DUROS+ calibration with M1263-III (2 tests), M1797, M1811 and HO298. Measured erosion volumes are plotted against predicted erosion volumes with DUROS+. Dotted line indicates that the measured and predicted erosion volumes are the same.

Landward side
The upward slope on landward side is fixed at 1:1.

As stated before, the erosion profile is dependent on wave height and grain size. The effect of the grain size and the wave height on the erosion profile is described below. In later elaboration of the dune erosion model the effect of the wave period was added (van Gent et al, 2008).

Grain size
The effect of the grain size on the erosion profile is described by the fall velocity as indicated in the scale relation:

$$n_l / n_d = \left(n_d / n_w^2\right)^{0.28} \qquad \text{(A 1.3)}$$

The fall velocity is gathered with the relation:

$$^{10}\log\left(\frac{1}{w_s}\right) = 0.476\left(^{10}\log D_{50}\right)^2 + 2.180\,^{10}\log D_{50} + 3.226$$ (WL|Delft Hydraulics, 1981) (A 1.4)

Situations with identical hydraulic conditions, the scale factor n_d equals 1, the grain size dependency becomes:

$$n_l = \left(n_w\right)^{-0.56} \quad \text{(A 1.5)}$$

$$x_{ref} = x_{scale}\left(\frac{w_{s,ref}}{w_{s,scale}}\right)^{-0.56} = x_{scale}\left(\frac{w_{s,scale}}{0.0268}\right)^{0.56} \quad \text{(A 1.6)}$$

So, coarser sediment goes with a steeper profile. The effect of the fall velocity can be described in the erosion profile by introducing the scale factor for the fall velocity in the parameter describing the length scale of the profile ([…] x). A D_{50} of 225µm corresponds with a fall velocity of 0.0268m/s (for fresh water with T≈10°C (Deltaflume conditions)). Thus including relation (A 1.6) in (A 1.2) becomes:

$$y_{scale} = 0.47\left[\left(\frac{w_{s,scale}}{0.0268}\right)^{0.56} x_{scale} + 18\right]^{0.5} - 2.00 \quad \text{(A 1.7)}$$

<u>Wave height</u>

The equilibrium profile holds for conditions with H_{0s}=7.6m. The relations between the wave height and the vertical and horizontal dimensions of the erosion profile are described by

$$n_d = n_H = n_L = n_T^2 \quad \text{(A 1.8)}$$

And by:

$$n_l = n_d^{1.28} \quad \text{(A 1.9)}$$

For conditions with constant wave steepness (H/L) and a constant fall velocity (w_s) the effect of wave height is described for the depth scale by:

$$n_d = n_H \quad \text{(A 1.10)}$$

$$y_{ref} = y_{scale}\left(\frac{H_{0s,ref}}{H_{0s,scale}}\right) = y_{scale}\left(\frac{7.6}{H_{0s,scale}}\right) \quad \text{(A 1.11)}$$

And for the length scale by:

$$n_l = n_H^{1.28} \quad \text{(A 1.12)}$$

$$x_{ref} = x_{scale}\left(\frac{H_{0s,ref}}{H_{0s,scale}}\right)^{1.28} = x_{scale}\left(\frac{7.6}{H_{0s,scale}}\right)^{1.28} \quad \text{(A 1.13)}$$

Combining relation (A 1.11) and (A 1.13) with (A 1.2) yields:

$$\left(\frac{7.6}{H_{0s,scale}}\right) y_{scale} = 0.47\left[\left(\frac{7.6}{H_{0s,scale}}\right)^{1.28} x_{scale} + 18\right]^{0.5} - 2.00 \quad \text{(A 1.14)}$$

Wave period
Later, the effect of the wave period has been implemented in the model of Vellinga. The wave period affects the length of the profile with the relation:

$n_l = n_T^{0.45}$ (Van Gent et al., 2008) (A 1.15)

Combining relation **Error! Reference source not found.** with **Error! Reference source not found.** yields;

$$y_{scale} = 0.4714\left[\left(\frac{12}{T_{p,scale}}\right)^{0.45} x_{scale} + 18\right]^{0.5} - 2.00 \quad \text{(A 1.16)}$$

DUROS model
The effect of the grain size, wave height and wave period can be described in one formula by combining relation (A 1.6), (A 1.14) and (A 1.16). Then the parabolic ‘equilibrium’ profile is described by:

$$\left(\frac{7.6}{H_{0s}}\right) y = 0.4714\left[\left(\frac{7.6}{H_{0s}}\right)^{1.28}\left(\frac{12}{T_p}\right)^{0.45}\left(\frac{w_s}{0.0268}\right)^{0.56} x + 18\right]^{0.5} - 2.00 \quad \text{(A 1.17)}$$

With the extent of the profile in x-direction and y-direction:

$$x_{\max} = 250\left(\frac{H_{0s}}{7.6}\right)^{1.28}\left(\frac{0.0268}{w_s}\right)^{0.56} \quad \text{(A 1.18)}$$

$$y_{\max} = \left[0.4714\left\{250\left(\frac{12}{T_p}\right)^{0.45} + 18\right\}^{0.5} - 2.00\right]\left(\frac{H_{0s}}{7.6}\right) \quad \text{(A 1.19)}$$

Development & further elaboration
The DUROS model has its origin in 1977 and is currently still being used and changed. In figure A-1.6 is the history of the DUROS plotted in a time-line. In section 5.2.3 a new DUROS version is introduced, in which a run-up formula is added.

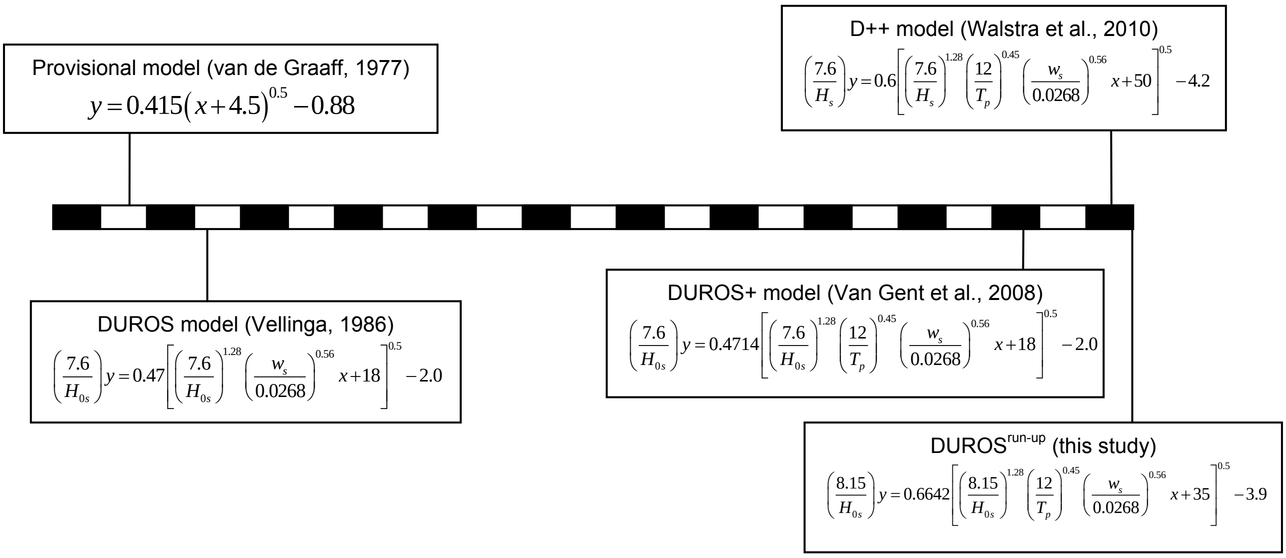


Figure A-1.6: Development of the erosion model DUROS.

A.1.2 Renew DUROS model

The present DUROS-model that was evaluated in section 5.2.2 performs with regard to profile development very poor in the region above the storm surge level (see figure 5.3). The assumed dune slope of 1:1 seems to disagree with the run-up shape that can be noted when examining different laboratory profiles. In the former model conversion (Vellinga, 1986), it was recommended to investigate the effect of the wave run-up.
The comparison of the DUROS-model with the laboratory experiments showed that the model underrates the slope of the (erosion) profile for each depth scale. In the previous section, it was found that the conversion of laboratory profiles to a prototype profile is performed with an average α of 0.39 instead of Vellinga's distortion coefficient of α=0.28. In this section, the deduction of the parabolic prototype profile was performed once again, now with α=0.28.

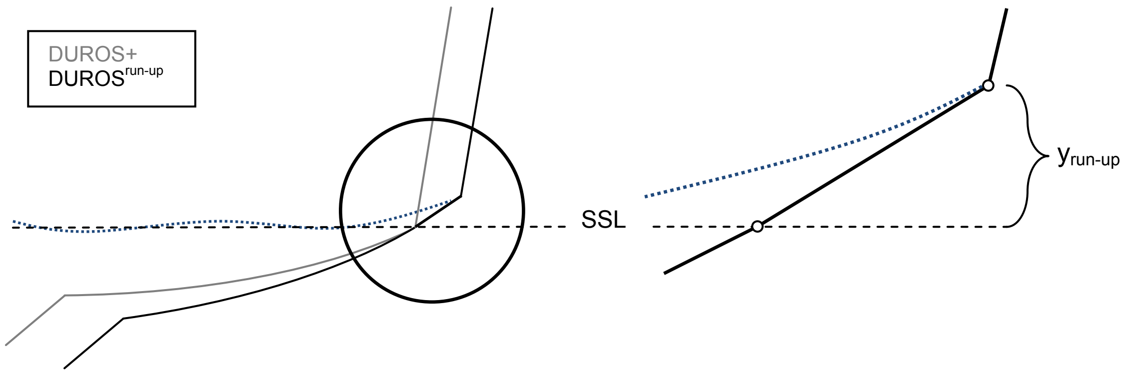
The renewed DUROS version contains the next two assumptions:

- A new <u>general equilibrium prototype profile</u> was created with large-scale experimental results and the distortion relation of Vellinga (1986), and
- <u>Run-up zone</u>: A run-up zone is introduced that is dependent on the wave conditions and foreshore slope.

Both the run-up formulation and the renewed parabolic prototype profile were implemented in the DUROS-model, resulting in the DUROS research version.

Run-up formula

During analysis of lab experiments in chapter 3, the run-up bed slope was found to be very similar for the experiments on the same scale. Also the run-up height was found to be similar and can be reproduced by a new run-up formula (proposed in section 3.3). The run-up zone is schematized below:



In section 3.4, a formula was derived for the wave run-up height. The run-up height is dependent on the wave period (T_p), wave height (H_s), the run-up bed slope and the foreshore slope (see relation (3.10)). This formula was implemented in the DUROS-model (see figure A-1.10).

Parabolic prototype profile
For the conversion of laboratory profiles to a general prototype profile, only the large-scale laboratory experiments (Test-1 & Test-2) were used. The argument for this choice is that depth scale n_d=5 is closest to prototype scale and therefore the most representative for (dune) erosion processes on prototype.
The profile measurements after 1.0h and 3.0h were (horizontally) averaged and converted to prototype with the distortion relation (2.32) in which n_w=1.

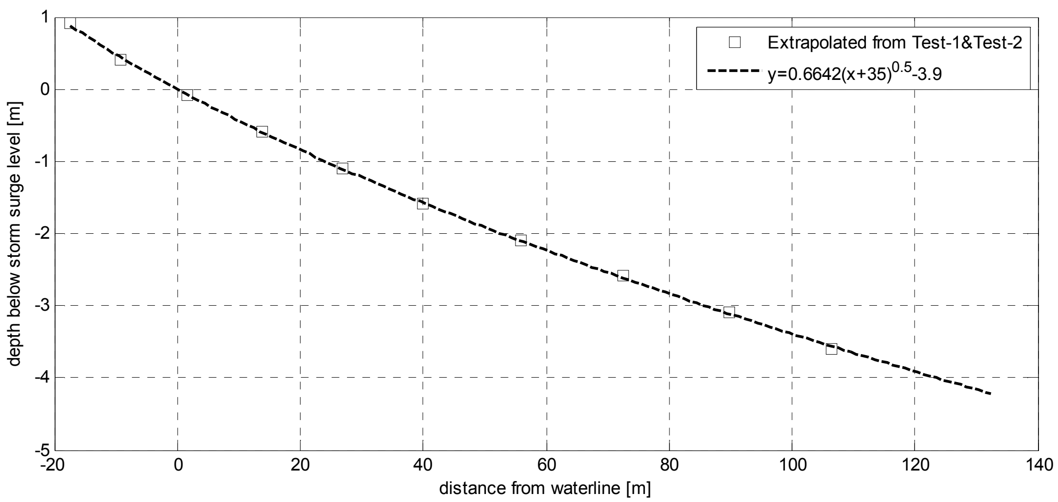


Figure A-1.7: Prototype erosion profile by extrapolation of large-scale experiments.

The shape of the parabolic profile in the DUROS-model is described with relation:

$$y = a\left(x+b\right)^{c} + d \qquad \text{(A 1.20)}$$

The profile was created by fitting relation (A 1.20) from the (prototype) wave run-up point (see table 3.5) to approximately -3.5 below SSL. The fitting led to new values a,b,c and d. They are listed in table A-1.3, together with the parameters of earlier DUROS versions. In Figure A-1.8, the equilibrium profiles of the different DUROS versions are plotted.

Model version	a	b	c	d
DUROS	0.47	18	0.5	-2.0
DUROS+	0.4714	18	0.5	-2.0
D++	0.6	50	0.5	-4.2
DUROS research version	0.6642	35	0.5	-3.9

Table A-1.3:Model characteristics of the different DUROS versions.

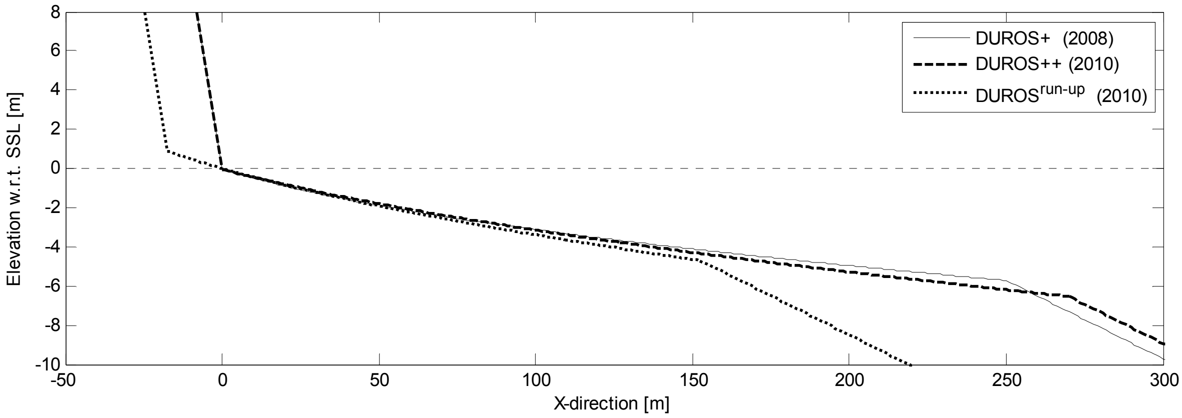


Figure A-1.8: Prototype equilibrium profiles with reference conditions in different DUROS versions.

Model calibration

The run-up algorithm and the renewed parabolic profile can now been implemented in the DUROS-model. This results in the next formulation for the new model:

$$\left(\frac{8.15}{H_{0s}}\right)y = 0.6642\left[\left(\frac{8.15}{H_{0s}}\right)^{1.28}\left(\frac{12}{T_p}\right)^{0.45}\left(\frac{w_s}{0.0268}\right)^{0.56} x+35\right]^{0.5} -3.9 \qquad \text{(A 1.21)}$$

The ‘reference wave height’ was changed to 8.15m (average of Test-1 & Test-2). After implementation, the model was be calibrated by adjusting the reference distance of the parabolic profile. An optimal agreement between measured and predicted erosion volumes was found when the parabolic profile was cut off at 170m in seaward direction from the water line. The results are shown in table A-1.4 and figure A-1.9.

Model	Parabolic coefficients		x_{ref}	Calibration performance (R)	Verification performance (R)	Comment
DUROS+	0.4714	18	250	0.999	0.901	
DUROS^{run-up}	0.6642	35	160	0.990	n/a	Run-up zone

Table A-1. 4: Result of the DUROS model calibration and model verification*

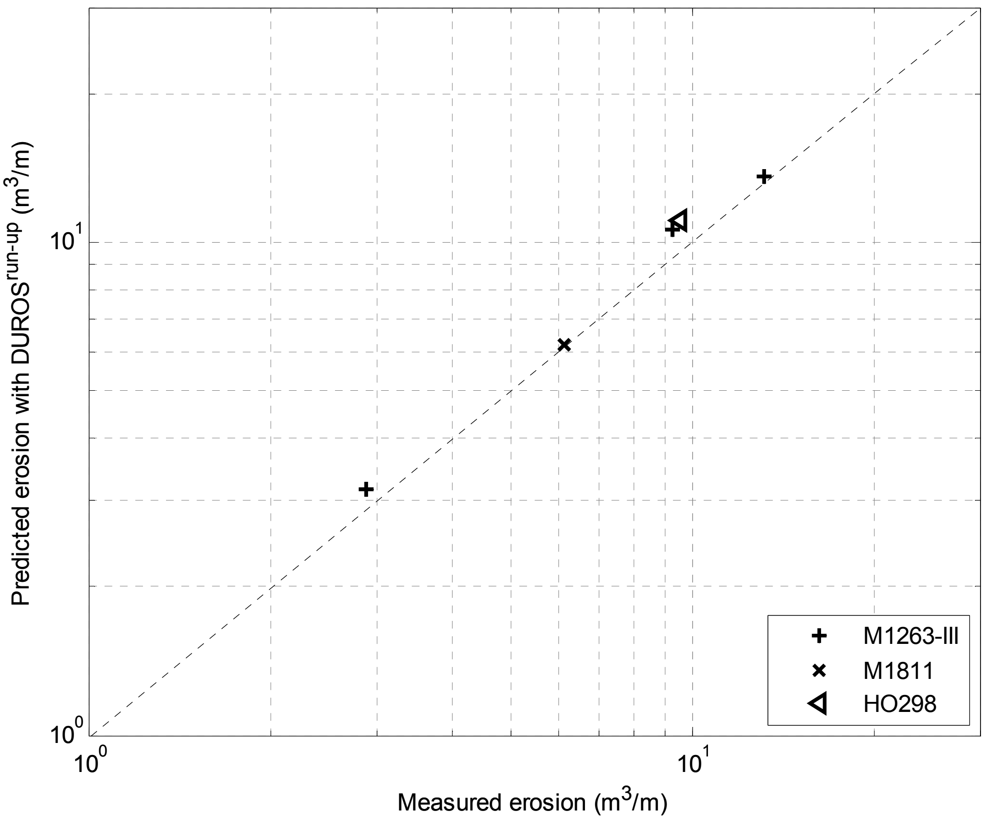


Figure A-1.9: Result of DUROS research version calibration with M1263-III (3 tests), M1797, M1811 and HO298. Measured erosion volumes are plotted against predicted erosion volumes. Dotted line indicates that the measured and predicted erosion volumes are the same.

A.1.2.1 *Conclusion*

The current DUROS model is in fact an erosion *volume* model that has as goal to predict erosion amounts on prototype scale. The model was created with the results of several small-scale and large-scale experiments. The calibration was performed with large-scale experiments.

In section 5.2 the DUROS model was compared with the experiments the model was initially deduced from. The results of the verification show that the erosion amounts are in agreement with the measurements of large-scale experiments. However, the model underestimates the erosion amounts for small-scale experiments. The shape of the predicted profiles is for all scales too gentle, and it was therefore hypothesised that the general parabolic prototype profile in DUROS is too gentle. The dune foot, which is fixed at the surge level, is too low for all scales. It was therefore stated that the run-up effect was not taken along in the model. It was recommended to include this run-up zone in the model.

With the insights from the analysis of the experimental data and the model verification, the current DUROS-model was modified. The new DUROS-model contains a new parabolic profile and a run-up formulation. The parabolic prototype profile was created with results of large scale experiments and the distortion relation of Vellinga (1986). The run-up formulation is characterized by an extension of the parabolic profile above the storm surge. The height of the run-up zone was described by a renewed run-up formula (see section 3.4). After implementation the new model was calibrated with the large scale experiments.

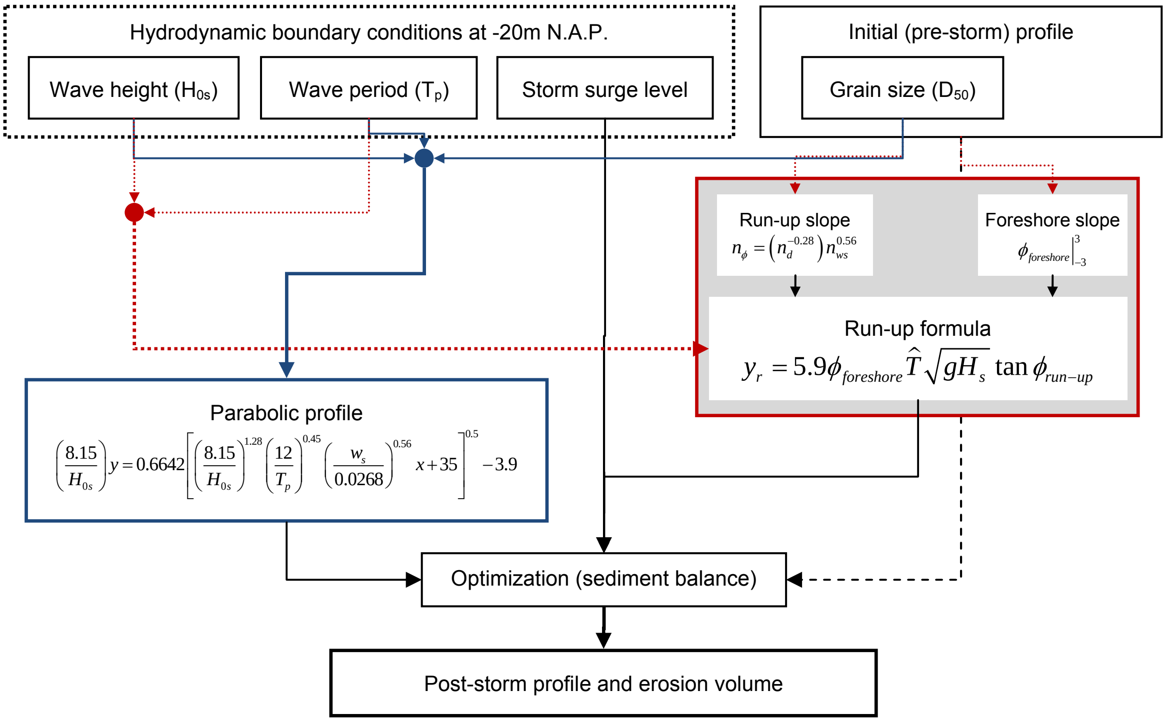


Figure A-1.10: Model structure DUROS research model.

A.2 XBeach parameter file (*"params.txt"*)

Grid input

nx = 178	Amount of grid points in x-direction (minus 1)
ny = 2	Amount of grid points in y-direction (minus 1)
depfile = h.dep	Name of the input profile, dimension=(ny+1,nx+1)
if vardx = 0	
dx = 1	Distance between x-points (constant)
dy = 5.0	Distance between y-points (constant)
else vardx = 1 xfile = xgr.dep	Variable x-grid, dimension=(ny+1,nx+1)
yfile = ygr.dep	Variable y-grid, dimension=(ny+1,nx+1)
xori = 41.	Origin of the coordinates
yori = 0.	Origin of the coordinates
alfa = 0.	Rotation
posdwn = -1	Direction of the z-axis (-1=positive up)
thetamin = -180	Lower directional limit, angle w.r.t. computational x-axis
thetamax = 180	Upper directional limit, angle w.r.t. computational x-axis
dtheta = 360	Directional resolution

Physical constants

rho = 1000	Density of water
g = 9.81	Gravitational acceleration

Time management

tstart = 1000	Start time of the simulation
tintg = 1	Time interval output global values
tstop = 22600 (6h)	Stop time simulation
CFL = 0.7	Maximum courrant number, actual number varies during calculation

Wave input

scheme = 2	Switch numerical schemes for wave action balance (1=Upwind, 2=Lax Wendroff)
wci = 0	Wave current interaction option
break = 3	Option breaker formulation (3='Roelvink2')
gamma = 0.55	Breaker parameter in Baldock or Roelvink formulation
alpha = 1	Wave dissipation coefficient
n = 10	Power in Roelvink dissipation model
delta = 0	Fraction of wave height to add to water depth
roller = 1	Option roller model, Roller model is turned on by default
beta = 0.1	Breaker slope coefficient in roller model
instat = 4	Wave groups generated using a parametric (PM) spectrum
bcfile = PM.inp	Input file for spectral computations
Hm0 = 0.082	H_{m0} of the wave spectrum, significant wave height
fp = 0.76	Peak frequency of the wave spectrum
gammajsp = 1	Peak enhancement factor in the PM expression (JONSWAP=3.3)
s = 1024	Directional spreading coefficient, cosine law
mainang = 270	Main wave angle (in nautical terms)
fnyq = 3.82	Highest frequency used to create PM spectrum (5*fp)
rt = 1800	Record length
dtbc = 0.2	File time step

Flow input

C = 65	Chezy coefficient
nuh = 0.1	Horizontal background viscosity
nuhfac = 1.0	Viscosity coefficient for roller induced turbulent horizontal viscosity
ARC = 0	Active reflection compensation at seaward boundary (0=off, 1=on) (Deltaflume: ARC=1)
carspan = 0	Free long wave input (0=use c_g)
left = 1	Left lateral boundary condition (0=Neumann, 1=wall)
right = 1	Right lateral boundary condition (0=Neumann, 1=wall)
tideloc = 0	Number of input tidal time series
zs0 = 0.461	Initial water level
swtable = RF_table.txt	parameterisation of the wave-shape

Limiters

gammax = 5	Maximum allowed wave height over water depth, this cuts off the wave height numerically (gammax = Hrms/hmax)) (for small scale experiments: gammax=2)
hmin = 0.2*	Threshold water depth for concentration and return flow
eps = 0.01*	Threshold depth for drying and flooding

sed input

form = 2	Equilibrium sediment concentration formulation
turb = 2*	Equilibrium sediment concentration computation option (0=none, 1=wave averaged, 2=bore averaged)
lws = 1	Long wave stirring (0=off, 1=on)
rhos = 2650	Density of sediment (no pores)
por = 0.4	Porosity
facua = 0.10	calibration coefficient for intra short wave transport (asymmetry transport)
rfb = 1	Maximum wave surface slope is fed back in roller energy balance
D50 = 0.0002	Uniform D50 sediment diameter
D90 = 0.0003	Uniform D90 sediment diameter

Morphological updating and avalanching

morfac = 10*	Morphological factor
morstart = 1000	Start time of morphological updates
wetslp = 0.10*	Critical avalanching slope under water
dryslp = 1.0	Critical avalanching slope above water
hswitch = 0.10*	Water depth at the interface from wetslp to dryslp
dzmax = 0.003*	Maximum avalanche speed
Tsmin = 1*	Minimal adaption time for sediment concentrations

*Parameters should to be changed when applying the XBeach-model on different scales (prototype and laboratory).

A.3 Experiment overview

This section provides most valuable data of the experiments that is needed for verification and calibration of the two model concepts, DUROS and XBeach.

	Dimensions			**Hydronamics**						**Wave board**			**Morphology**
Casename	n_d	n_l	S_f	$W_{L,P}$	$W_{L,L}$	$T_{p,P}$	$T_{p,L}$	$H_{s,P}$	$H_{s,th}$	$Hs_{,wb}=h_{m0}$	f_p	$f_{nyq}=5*f_p$	$D_{50,th}$
'Test-1'	5,0	7,85	1,57	' '	4,200	12,1	5,40	8,3	1,669	**1,695**	0,19	0,93	0,000225
'Test-2'	5,0	7,85	1,57	' '	4,200	12,1	5,40	8,0	1,597	**1,7231**	0,19	0,93	0,000225
'Test-3'	5,0	7,85	1,57	' '	3,374	10,1	4,50	5,4	1,080	Variable	0,22	1,11	0,000225
'CT46'	26,0	61,81	2,38	5	0,806	12,0	2,35	7,7	0,298	**0,29**	0,42	2,12	0,000225
'CT73'	26,0	61,81	2,38	6	0,806	12,0	2,35	7,6	0,292		0,42	2,12	0,000225
'CT93'	26,0	61,81	2,38	5	0,806	9,0	1,76	7,6	0,292		0,57	2,84	0,000225
'CT97'	26,0	61,81	2,38	5	0,806	12,0	2,35	4,2	0,163		0,43	2,13	0,000225
'DT34'	26,0	61,81	2,38	5	0,806	12,0	2,35	7,6	0,292	**0,282**	0,42	2,12	0,000225
'DT48'	26,0	61,81	2,38	5	0,806	12,0	2,35	7,6	0,294	0,294	0,42	2,12	0,000225
'DT74'	26,0	61,81	2,38	5	0,806	12,0	2,35	7,6	0,291	**0,296**	0,42	2,12	0,000225
'DT94'	26,0	61,81	2,38	5	0,806	9,0	1,76	7,6	0,292		0,57	2,84	0,000225
'Test-121'	26,0	64,87	2,50	' '	0,806	12,0	2,35	7,8	0,301	0,301	0,43	2,13	0,000225
'Test-125'	26,0	64,33	2,47	' '	0,806	12,0	2,35	7,7	0,295	0,295	0,43	2,13	0,000225
'CT24'	46,6	130,56	2,80	5	0,585	12,0	1,76	8,0	0,172	**0,174**	0,57	2,85	0,000225
'CT26'	46,6	130,56	2,80	5	0,585	12,0	1,76	7,6	0,163	**0,16**	0,57	2,85	0,000225
'CT28'	46,6	130,56	2,80	5	0,585	12,0	1,76	7,6	0,163	**0,164**	0,57	2,85	0,000225
'DT98'	46,6	130,56	2,80	5	0,806	16,0	2,35	7,6	0,163		0,43	2,13	0,000225
'Test-101'	47,0	143,53	3,05	' '	0,585	12,1	1,76	7,7	0,163	**0,154**	0,57	2,84	0,000225
'Test-105'	47,0	143,53	3,05	' '	0,585	12,1	1,76	7,7	0,163	**0,161**	0,57	2,84	0,000225
'CT14'	83,6	275,77	3,30	5	0,461	12,0	1,31	7,4	0,089	0,089	0,76	3,81	0,000225
'CT16'	83,6	275,77	3,30	5	0,461	12,0	1,31	7,4	0,089	**0,091**	0,76	3,81	0,000225
'CT18'	83,6	275,77	3,30	5	0,461	12,0	1,31	7,6	0,091	0,091	0,76	3,81	0,000225
'CT63'	83,6	275,77	3,30	5	0,461	12,0	1,31	8,1	0,097	**0,098**	0,76	3,81	0,000225
'DT64'	83,6	275,77	3,30	5	0,461	12,0	1,31	8,1	0,097	**0,099**	0,76	3,81	0,000225
'Test-111'	84,0	295,28	3,52	' '	0,461	12,0	1,31	7,6	0,091	**0,082**	0,76	3,82	0,000225
'Test-115'	84,0	296,47	3,53	' '	0,461	12,0	1,31	7,6	0,091	**0,096**	0,76	3,82	0,000225

Table A-3.1: Characteristics of the laboratory experiments with similar sediment properties.

A.4 XBeach (input changes)

A.4.1 Model grid set-up

The generic Matlab-script provides XBeach input bathymetry with constant grid size in the x-direction (along the wave flume). However, to reduce the computation duration for the XBeach-model, a variable grid can be applied in which the grid will be minimized for bed activity (in the near shore and dune-zone).

A.4.2 Wave spectrum

During the test program the wave board is configured to generate a wave climate that is similar to the North Sea wave climate. This wave climate can be modeled with the JON SWAP spectrum (PM-variant). Default settings consist of a Nyquist frequency of 1Hz. As the figure A-4.1 indicates, the default Nyquist frequency affects the wave spectrum at the wave board.

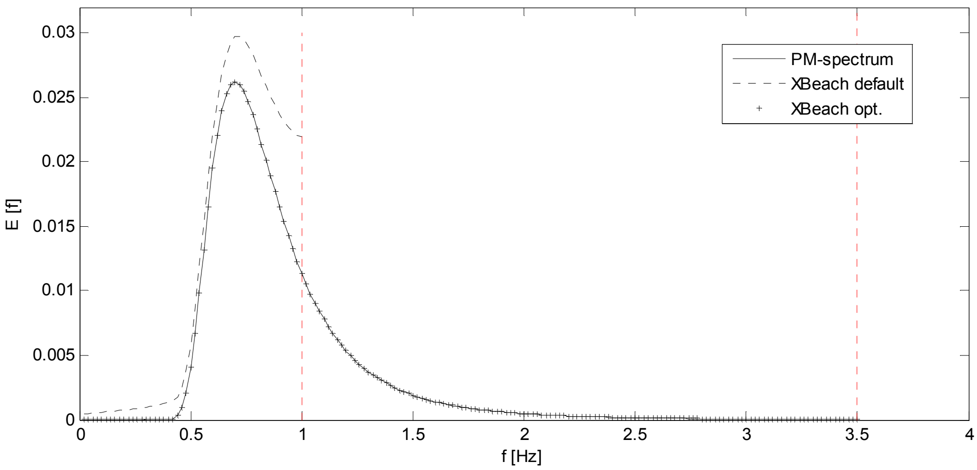


*Figure A-4.1: Pierson Moskowitz (PM) wave spectrum that is applied in XBeach for the North Sea. The dotted line is the default spectrum. The plus-sign indicates the adjusted spectrum in which f_{nyq}=5*f_p.*

Literature research shows that a commonly used Nyquist frequency of 5*f_p. The figure above indicates that is the adjusted wave spectrum is identical with the normal PM-spectrum. In figure A-4.1, the simulated wave climate with and without adjusted nyquist are shown.

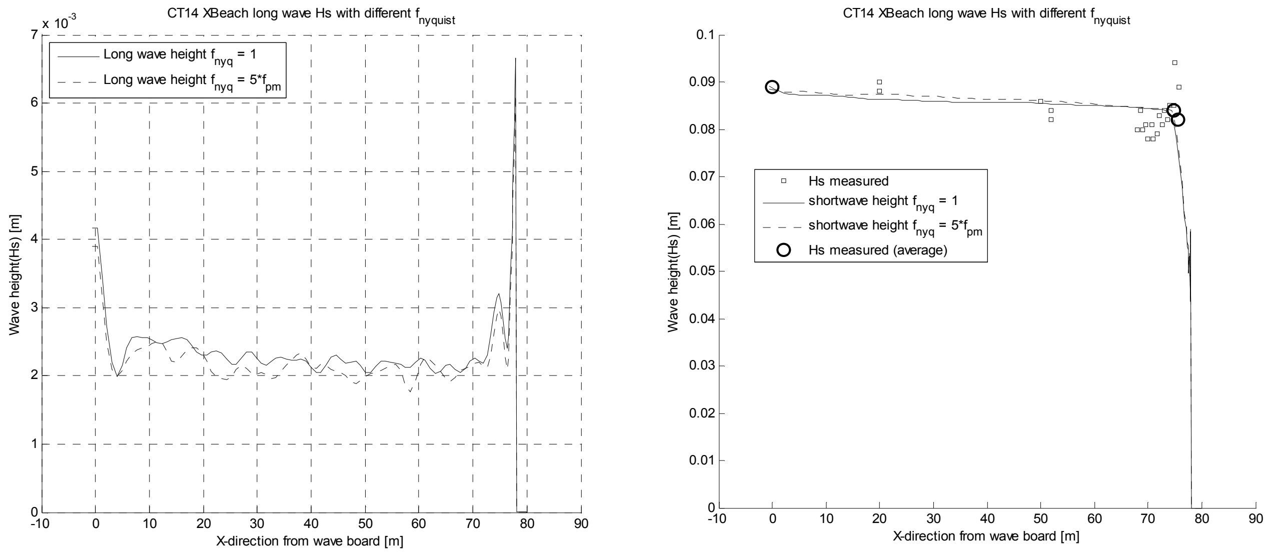


Figure A-4.2: Wave heights in the experiment CT14 (M1263-I) with and without adjusted nyquist. Left panel: The simulated long wave heights with XBeach. Right panel: The simulated (experiment-averaged) shortwave height (H_s) with XBeach and the measured (interval & experiment-averaged) wave heights (H_s).

The effect of the nyquist frequency on the longwave and shortwave height shows to be minimal.

A.4.3 Active Reflection Component (ARC)

The ARC component of the wave board is default set 'on'. A review of the M1263 reports shows that no such setting is applied for the wave board. Therefore, this setting is changed in the XBeach input file. The result for long and short wave heights are shown in the figure below.

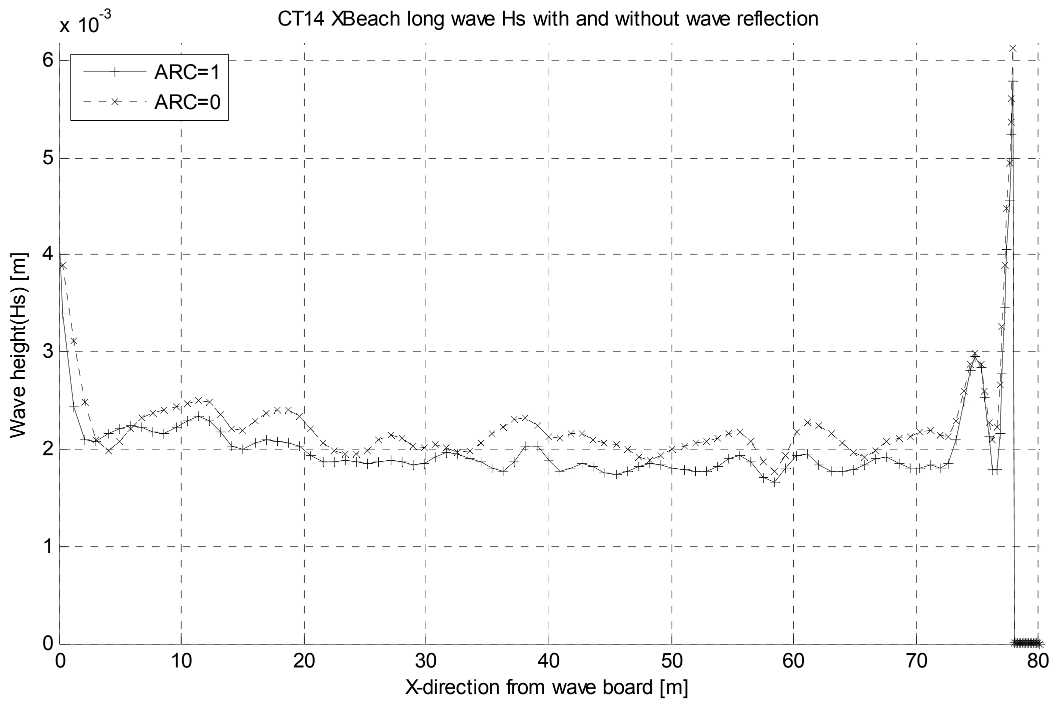


Figure A-4.3: Effect of ARC on the long wave height (in experiment CT14). Solid lines are with ARC-component. Dotted lines are without ARC.

The absence of an ARC component leads to comparable short wave heights. The long wave height deviates from the simulation without ARC in the wave flume. However, at the beach profile, the long wave heights are comparable. As the long wave height at the beach affects the avalanching, it is assumed that the presence (or absence) of the ARC does not affect the sediment transport.

A.5 Sediment transport in XBeach

A.5.1 Sediment transport

Advection-diffusion scheme
The sediment transport is modeled with a depth-averaged advection diffusion equation [Galappatti and Vreugdenhil, 1985]:

$$\frac{\partial hC}{\partial t}+\frac{\partial hCu^E}{\partial x}+\frac{\partial hCv^E}{\partial y}+\frac{\partial}{\partial x}\left[D_h h\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_h h\frac{\partial C}{\partial y}\right]=\frac{hC_{eq}-hC}{T_s} \tag{A.5.1}$$

where C represents the depth-averaged sediment concentration which varies on the wave-group time scale, and D_h is the sediment diffusion coefficient. The entrainment of the sediment is represented by an adaptation time T_s, given by a simple approximation based on the local water depth, h, and sediment fall velocity w_s:

$$T_s=\max\left(0.05\frac{h}{w_s},T_{s,\min}\right)s \tag{A.5.2}$$

where a small value of T_s corresponds to nearly instantaneous sediment response. In this expression T_{smin} is a user specified adaption time (default set at 1.0 second). The entrainment or deposition of sediment is determined by the mismatch between the actual sediment concentration, C, and the equilibrium concentration, C_{eq}, thus representing the source term in the sediment transport equation.

The bed-updating is discussed next. Based on the gradients in the sediment transport the bed level changes according to:

$$\frac{\partial z_b}{\partial t}+\frac{f_{mor}}{(1-p)}\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}\right)=0 \tag{A.5.3}$$

where p is the porosity, f_{mor} is a morphological acceleration factor of O(1-10) (e.g. Reniers et al., 2004a) and q_x and q_y represent the sediment transport rates in x- and y-direction respectively, given by:

$$q_x(x,y,t)=\left[\frac{\partial hCu^E}{\partial x}\right]+\left[\frac{\partial}{\partial x}\left[D_h h\frac{\partial C}{\partial x}\right]\right] \tag{A.5.4}$$

$$q_y(x,y,t)=\left[\frac{\partial hCv^E}{\partial y}\right]+\left[\frac{\partial}{\partial y}\left[D_h h\frac{\partial C}{\partial y}\right]\right] \tag{A.5.5}$$

To account for bed-slope effects on sediment transport a bed-slope correction factor f_{slope} is introduced.

Transport formulations
The equilibrium sediment concentration C_{eq} is calculated with an extended transport formulation of Van Rijn (2007):

$$C_{eq} = \frac{A_{sb}}{h}\left(\left(|u^E|^2 + 0.64u_{rms,2}^2\right)^{0.5} - u_{cr}\right)^{1.5} + \frac{A_{ss}}{h}\left(\left(|u^E|^2 + 0.64u_{rms,2}^2\right)^{0.5} - u_{cr}\right)^{2.4} \qquad \text{(A.5.6)}$$

where sediment is stirred by the Eulerian mean and infragravity velocity (u^E) in combination with the near bed short wave orbital flow, $u_{rms,2}$. In the default mode, the sediment is stirred due to mean and infragravity velocities (u^E). By setting *lws = 0* the mean component can be excluded. The shortwave stirring can be turned off by setting *sws = 0*. By default *sws = 1*.
The effect of near-bed wave breaking induced turbulence is included via the short wave orbital flow (Reniers et al., 2004a):

$$u_{rms,2} = \left(u_{rms}^2 + 1.45k_b\right)^{0.5} \qquad \text{(A.5.7)}$$

In which k_b, is the bore-averaged near-bed turbulence energy. By setting turb=0, the effect of wave breaking induced turbulence is turned off. By setting turb=1, the induced turbulence is wave averaged. By default the induced turbulence is bore-averaged (see Van Thiel de Vries (2009) for details).

The u_{rms} obtained from the wave-group varying wave energy using linear wave theory as

$$\mathrm{u_{rms}} = \frac{\pi H_{rms}}{T_{rep}\sqrt{2}\sinh(kh + \delta H_{rms})} \qquad \text{(A.5.8)}$$

The combined mean/infragravity and orbital flow velocity have to exceed a threshold value, u_{cr}, before sediment is set in motion (see A-5.2).
To account for bed-slope effects on the equilibrium sediment concentration a bed-slope correction factor is introduced, where the bed-slope is denoted by *m* and α_b represents a calibration factor. The bed load coefficients A_{sb} and the suspended load coefficient A_{ss} are functions of the sediment grain size, relative density of the sediment, the dimensionless particle size and the local water depth:

$$A_{sb} = \frac{0.015h\rho_s\left(D_{50}/h\right)^{1.2}}{\left((s-1)gD_{50}\right)^{0.75}} \qquad \text{(A.5.9)}$$

$$A_{ss} = \frac{0.012D_{50}\rho_s D_*^{-0.6}}{\left((s-1)gD_{50}\right)^{1.2}} \qquad \text{(A.5.10)}$$

Note that the transport model does not contain transport contributions related to wave skewness.

The Soulsby-Van Rijn formulation is not strictly valid for sheet flow conditions. If applied in high velocity situations, the formulation as used in XBeach leads to unrealistically high sediment transport rates. In order to compensate this, steady flow velocities used to mobilize sediment are limited by an upper-bound Shields parameter for the start of sheet flow
(θ_{sf} = 0.8 – 1.0):

$$u_{flow,stirring}^2 = \min\left(\left(u^E\right)^2 + \left(v^E\right)^2, \theta_{sf}\frac{gD_{50}\Delta}{c_f}\right)$$

(A.5.11)

This approach assumes that in sheet flow conditions higher velocities lead to higher sediment transport rates, but not to higher equilibrium sediment concentrations, which is not necessarily correct. However, the assumption does cause sediment discharge under sheet flow conditions to become a linear function of flow discharge, which is in line with Kobayashi et al. (1996).

A.5.2 Critical velocity for initiation of motion/suspension

The critical depth averaged velocity can be derived from the critical bed-shear stress using the Chézy equation (Van Rijn, 1993):

$$\bar{u}_{cr} = 5.75 u_{*,cr} \log 10\left(\frac{12h}{k_s}\right) \quad \text{(A.5.12)}$$

$\bar{u}$		Depth-averaged critical velocity	[ms^{-1}]
$u_{*,cr}$	$= \theta_{cr}^{0.5}\left((s-1)gD_{50}\right)^{0.5}$	Critical bed-shear velocity	[ms^{-1}]
k_s	$= \alpha D_{90}$	Effective bed roughness of a flat bed	[m]
α		Coefficient (α=3 for sand and gravel material)	[-]

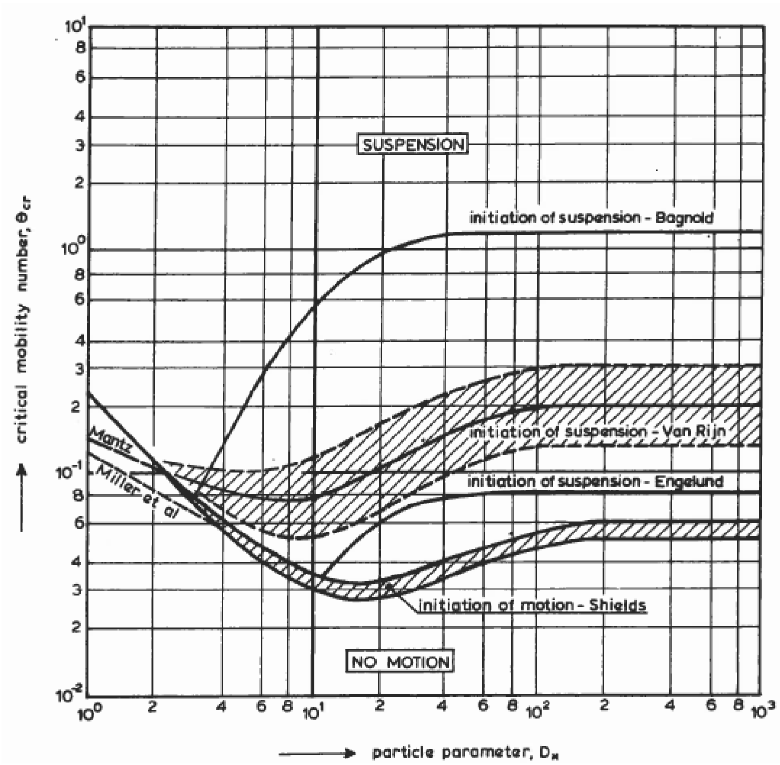


Figure A-5.1: Initiation of motion and suspension for a current over a plane bed (Van Rijn, 1989).

The Shields curve (1936) was used to represent the critical conditions for initiation of *motion* (see figure A-5.1). Bonnefille (1963) and Yalin (1972) showed that the Shield curve can be expressed in terms of the dimensionless mobility parameter θ and the dimensionless particle diameter D_*.
An experimental investigation was carried out at Delft Hydraulics (1984) to determine the critical flow conditions for initiation of *suspension*. The initiation of suspension was defined as the stage of flow at which particles perform a jump length larger than about 100 particle diameters (Van Rijn, 1993).

Both the relations for the mobility parameter for *motion* and the relations for the mobility parameter of *suspension* are summarised in table below.

Dimensionless parameter D_*	Mobility parameter for motion θ_{cr}	Mobility parameter for suspension θ_{crs}
$1 < D_* \leq 4$	$\theta_{cr} = 0.24 D_*^{-1}$	$\theta_{crs} = \frac{16}{D_*^2} \frac{w_s^2}{(s-1) g D_{50}}$
$4 < D_* \leq 10$	$\theta_{cr} = 0.14 D_*^{-0.64}$	
$10 < D_* \leq 20$	$\theta_{cr} = 0.04 D_*^{-0.1}$	$\theta_{crs} = 0.16 \frac{w_s^2}{(s-1) g D_{50}}$
$20 < D_* \leq 150$	$\theta_{cr} = 0.013 D_*^{0.29}$	
$150 < D_*$	$\theta_{cr} = 0.055$	

The fall velocity of grains can be obtained with the fall velocity equations by Ahrens (2000) (also implemented in XBeach). The dimensionless particle is defined by:

$$D_* = \left[\frac{(s-1) g}{\nu^2} \right]^{1/3} D_{50} \tag{A.5.13}$$

With the kinematic viscosity v (see Ahrens, 2000). To determine the threshold depth-averaged speed required to *move* grains, Van Rijn (1984) simplified relation A-5.12 to:

$$\overline{U}_{cr} = 0.19 D_{50}^{0.1} \log 10 \left(\frac{4h}{D_{90}} \right) \text{ for } 100 \leq D_{50} \leq 500 \ \mu\text{m} \tag{A.5.14}$$

$$\overline{U}_{cr} = 8.5 D_{50}^{0.6} \log 10 \left(\frac{4h}{D_{90}} \right) \text{ for } 500 \leq D_{50} \leq 2000 \ \mu\text{m} \tag{A.5.15}$$

The formulas A-5.14 and A-5.15 are valid for fresh water (ρ_w=1000kgm^{-3}) at 15°C, sediment density (ρ_s=2650 kgm^{-3}) and gravitational acceleration (g=9.81ms^{-2}). The simplified relations were implemented in XBeach.

Next the sensitivity of the critical depth-averaged velocity equations to other conditions is analysed. Three formulas were analysed: The simplified formula for initiation of motion in XBeach, the formula for initiation of motion from the mobility parameter by Bonnefille and Yalin and the formula for initiation of suspension using the mobility parameter of Van Rijn (1984). The sensitivity to the grain size D_{50}, grain size ratio D_{90}/D_{50}, the water temperature (T) and the water depth (h) were analysed. Default conditions are D_{50}=225μm, D_{90}=375μm , T=15°C and h=0.5m. The results are shown in figure A-5.2.

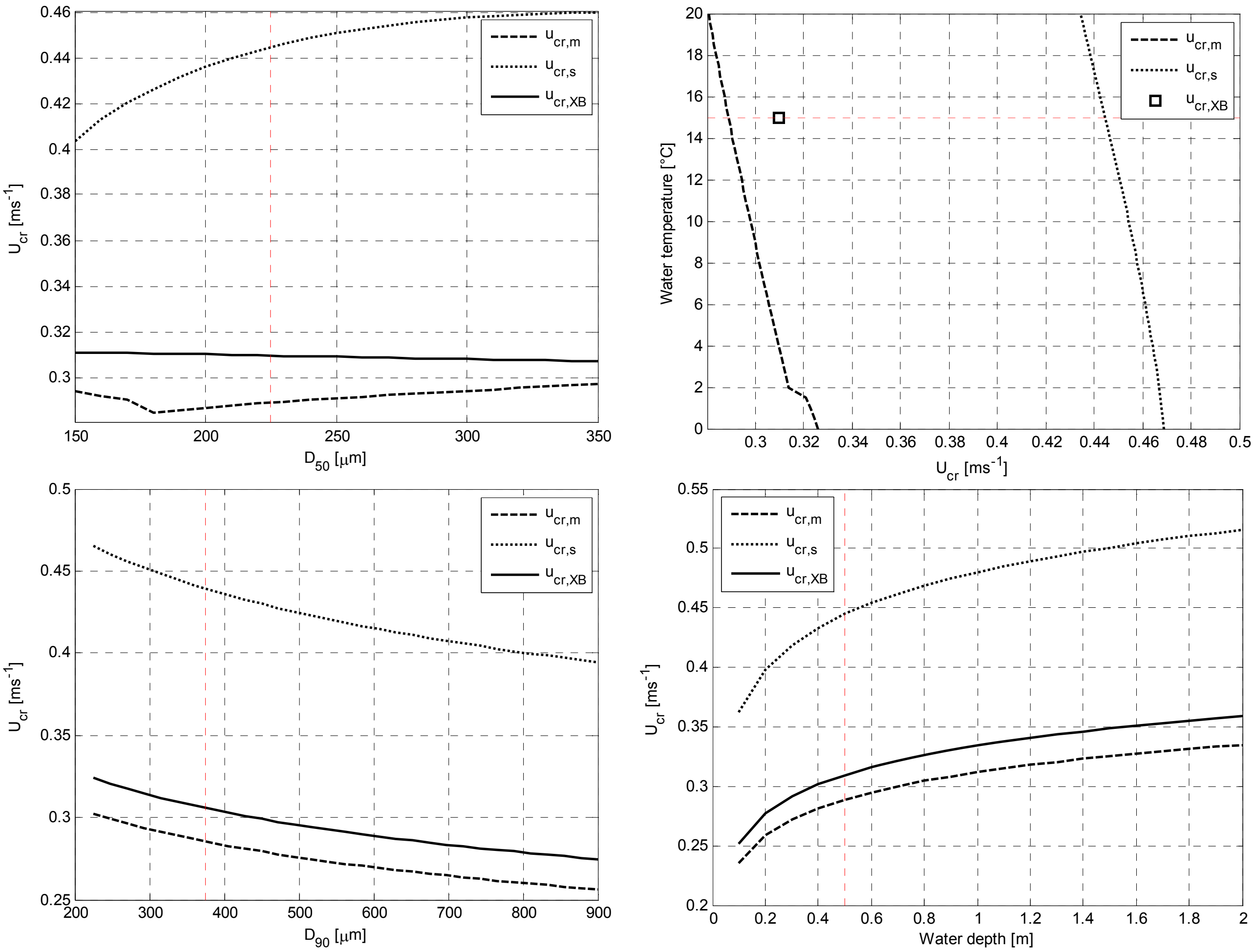


*Figure A-5.2: Critical depth-averaged velocity for initiation of motion and suspension. Solid lines represent the critical velocity in XBeach, the dashed and the dotted lines are the critical velocities for resp. initiation of motion and suspension. The Upper left panel: Sensitivity to D_{50} (D_{90}=D_{50}*1.5). Upper right panel: Sensitivity to the water temperature. Lower left panel: The sensitivity to changing D_{90}/D_{50} ratio. Lower right panel: Critical velocities in relation to the water depth.*

A.6 Results of XBeach calibration

SCENARIO 1: Selected morphological parameters (run003)

Process	XBeach parameter	Unit	Explanation	Default (n_d = 6)	Scale factor
Avalanche	A_{max}	m^3s/m	Maximum avalanche rate	0.003	$n_d n_L n_t = n_d n_L \sqrt{n_d} = S_f^{1.5}$
Avalanche	hswitch	m	Water depth at interface from wet slope to dry slope	0.10	S_f
Limiter	hmin	m	Threshold water depth for concentration and return flow	0.20	S_f
Limiter	eps	m	Threshold depth for drying and flooding	0.01	S_f

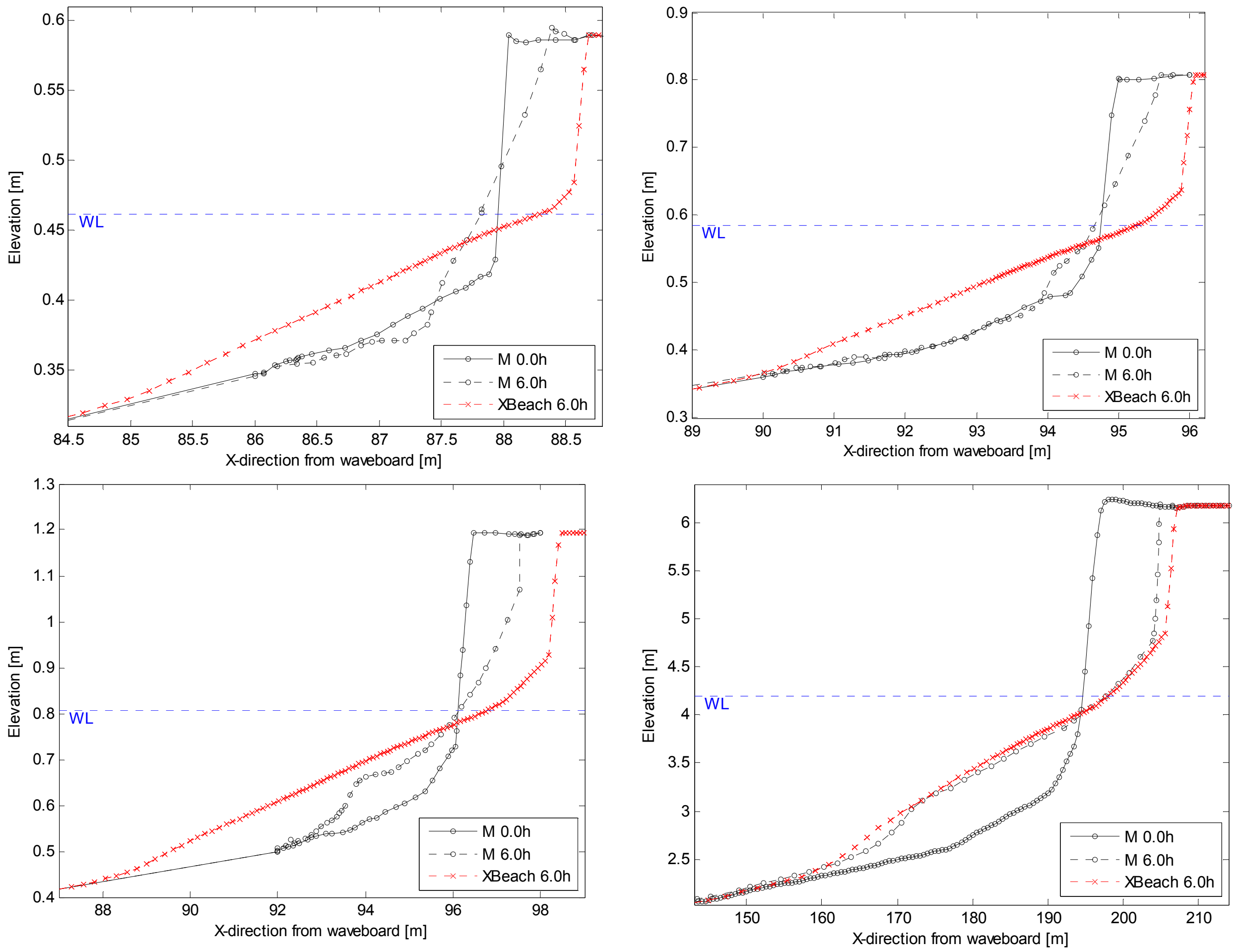


Figure A-6.1: XBeach model performance on four depth scales; predicted post-storm profiles on laboratory scale. The red dashed line represents the XBeach prediction, the black dashed line is the laboratory measurement and the blue dashed line is the water line. The legend box contains the prototype times of the measurements and predictions. Upper left panel: Laboratory experiment test-111 on depth scale 84. Upper right panel: Laboratory experiment test-101 on depth scale 47. Lower left panel: Laboratory experiment test-121 on depth scale 26. Lower right panel: Laboratory experiment test-1 on depth scale 5.

Scale	Experiment	Measured erosion volume [m^3/m]	Predicted erosion volume [m^3/m]	Measured dune retreat [m]	Predicted dune retreat [m]	BSS [-]
84	Test-111	0.017	0.074	0.31	0.63	-4.03
47	Test-101	0.066	0.224	0.57	1.07	-3.14
26	Test-121	0.32	0.70	1.12	1.99	0.02
5	Test-1	17.6	18.3	9.9	10.2	0.98

Table 0.1: XBeach performance: Measured and predicted laboratory erosion volume and dune retreat after 6h simulation time.

SCENARIO 2 without turbulence contribution (run004)

Morphologic parameters

Process	XBeach parameter	Unit	Explanation	Default (n_d = 6)	Scale factor
Avalanche	A_{max}	m^3s/m	Maximum avalanche rate	0.003	$n_d n_L n_t = n_d n_L \sqrt{n_d} = S_f^{1.5}$
Avalanche	hswitch	m	Water depth at interface from wet slope to dry slope	0.10	S_f
Limiter	hmin	m	Threshold water depth for concentration and return flow	0.20	S_f
Limiter	eps	m	Threshold depth for drying and flooding	0.01	S_f
Turb model	**Turb**	**-**	**Equilibrium sediment concentration computation option (0=none, 1=wave averaged, 2=bore averaged)**	**2**	**0**

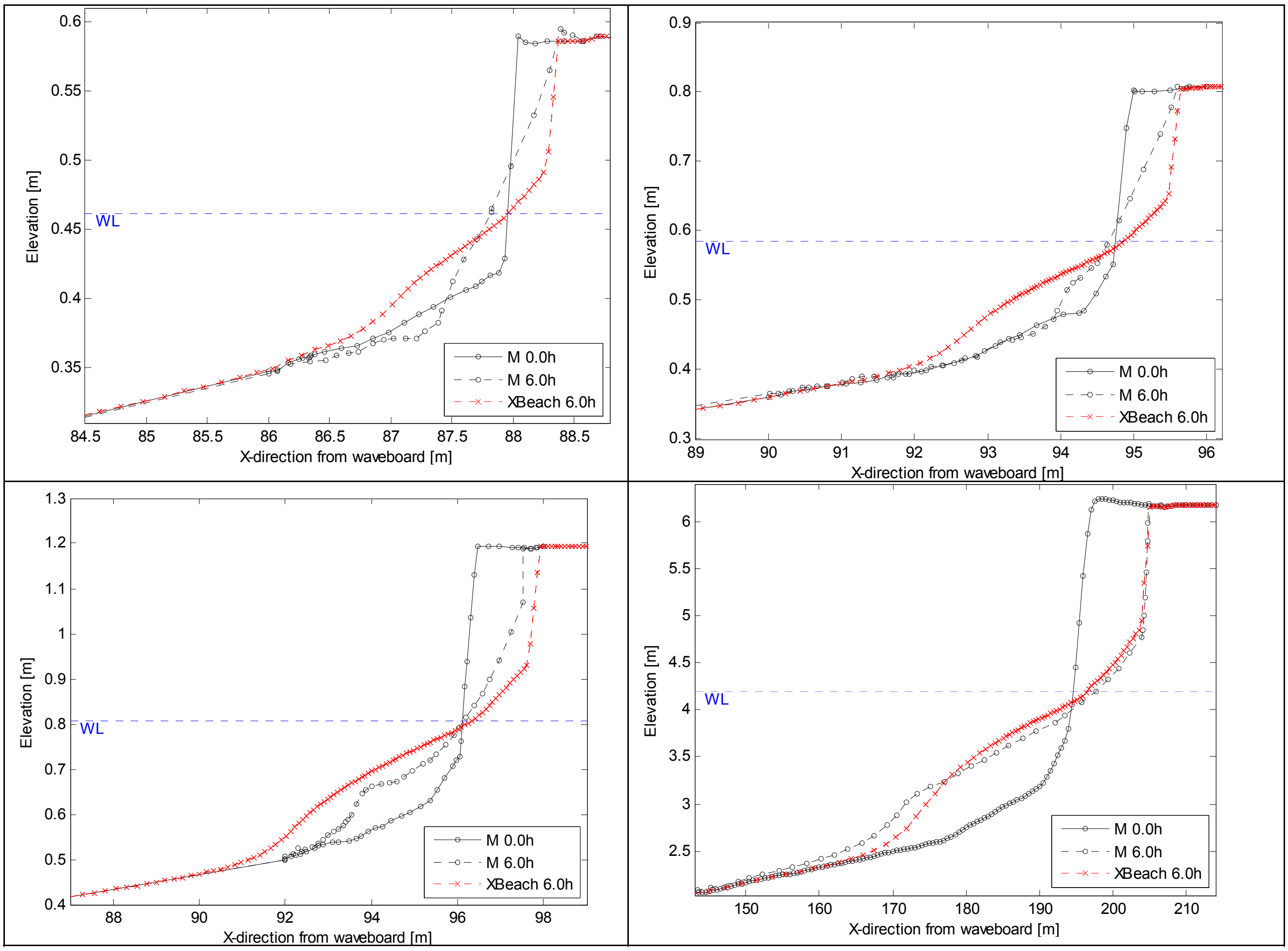


Figure A-6.2: XBeach model performance on four depth scales; predicted post-storm profiles on laboratory scale. The red dashed line represents the XBeach prediction, the black dashed line is the laboratory measurement and the blue dashed line is the water line. The legend box contains the prototype times of the measurements and predictions. Upper left panel: Laboratory experiment test-111 on depth scale 84. Upper right panel: Laboratory experiment test-101 on depth scale 47. Lower left panel: Laboratory experiment test-121 on depth scale 26. Lower right panel: Laboratory experiment test-1 on depth scale 5.

Scale	Experiment	Measured erosion volume [m^3/m]	Predicted erosion volume [m^3/m]	Measured dune retreat [m]	Predicted dune retreat [m]	BSS [-]
84	Test-111	0.017	0.034	0.31	0.32	-0.01
47	Test-101	0.066	0.128	0.57	0.66	-0.20
26	Test-121	0.32	0.48	1.12	1.46	0.65
5	Test-1	17.6	14.72	9.9	8.3	0.89

Table 0.2: XBeach performance: Measured and predicted laboratory erosion volume and dune retreat after 6h simulation time.

SCENARIO 3 scaling the critical wet slope (run005)

Morphologic parameters

Process	XBeach parameter	Unit	Explanation	Default (n_d = 6)	Scale factor
Avalanche	A_{max}	m^3s/m	Maximum avalanche rate	0.003	$n_d n_L n_t = n_d n_L \sqrt{n_d} = S_f^{1.5}$
Avalanche	hswitch	m	Water depth at interface from wet slope to dry slope	0.10	S_f
Avalanche	**Wetslp**	**-**	**Critical wet slope in avalanche algorithm**	**0.1**	$\mathbf{S_f^{-0.28}}$
Limiter	hmin	m	Threshold water depth for concentration and return flow	0.20	S_f
Limiter	eps	m	Threshold depth for drying and flooding	0.01	S_f
Turb model	Turb	-	Equilibrium sediment concentration computation option (0=none, 1=wave averaged, 2=bore averaged)	2	0

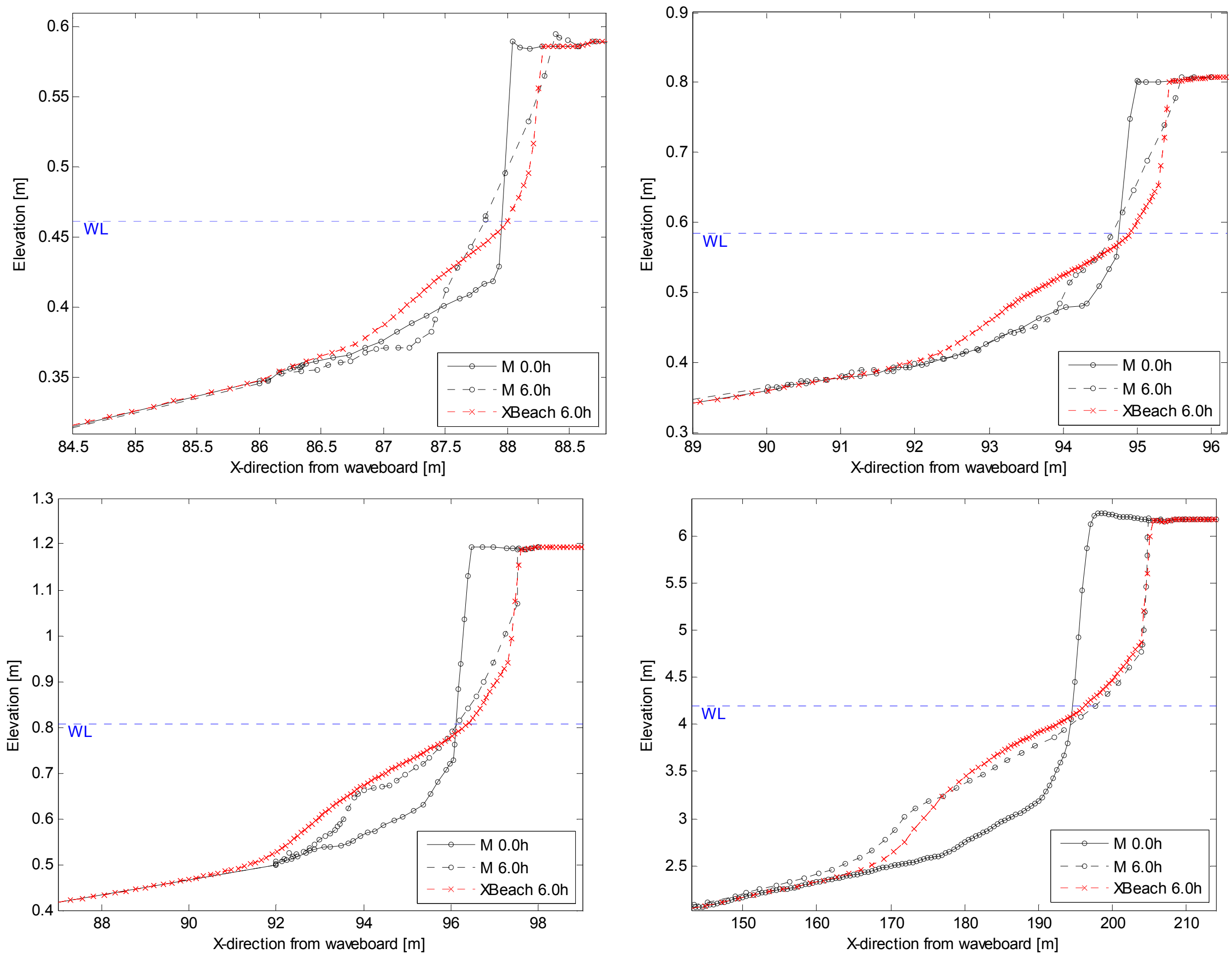


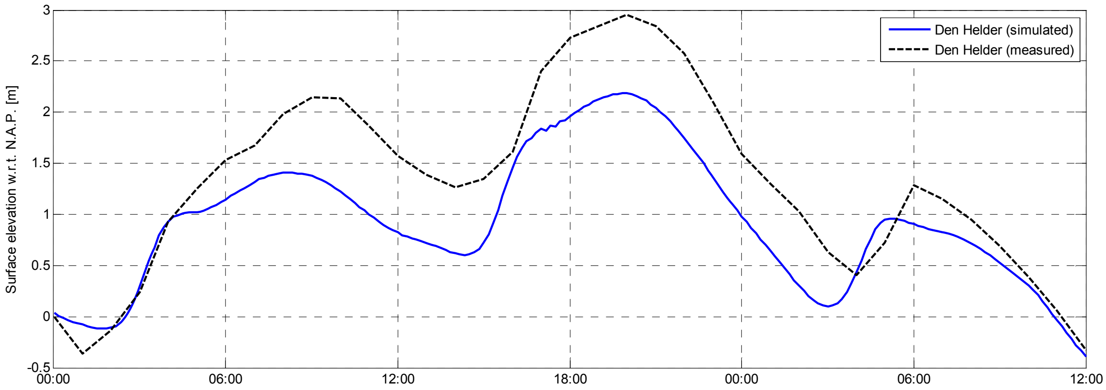
Figure A-6.3: XBeach model performance on four depth scales; predicted post-storm profiles on laboratory scale. The red dashed line represents the XBeach prediction, the black dashed line is the laboratory measurement and the blue dashed line is the water line. The legend box contains the prototype times of the measurements and predictions. Upper left panel: Laboratory experiment test-111 on depth scale 84. Upper right panel: Laboratory experiment test-101 on depth scale 47. Lower left panel: Laboratory experiment test-121 on depth scale 26. Lower right panel: Laboratory experiment test-1 on depth scale 5.

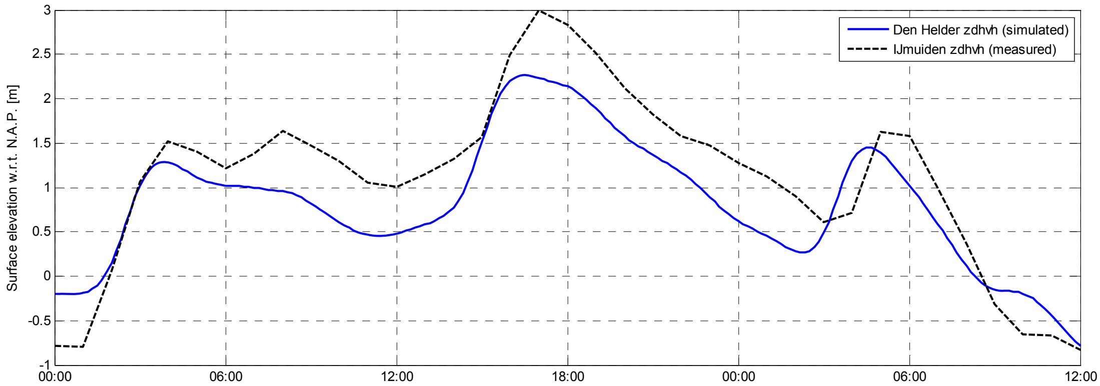
Scale	Experiment	Measured erosion volume [m^3/m]	Predicted erosion volume [m^3/m]	Measured dune retreat [m]	Predicted dune retreat [m]	BSS [-]
84	Test-111	0.017	0.024	0.31	0.24	0.43
47	Test-101	0.066	0.093	0.57	0.47	0.45
26	Test-121	0.32	0.38	1.12	1.12	0.93
5	Test-1	17.6	14.9	9.9	8.5	0.89

Table 0.3: XBeach performance: Measured and predicted laboratory erosion volume and dune retreat after 6h simulation time.

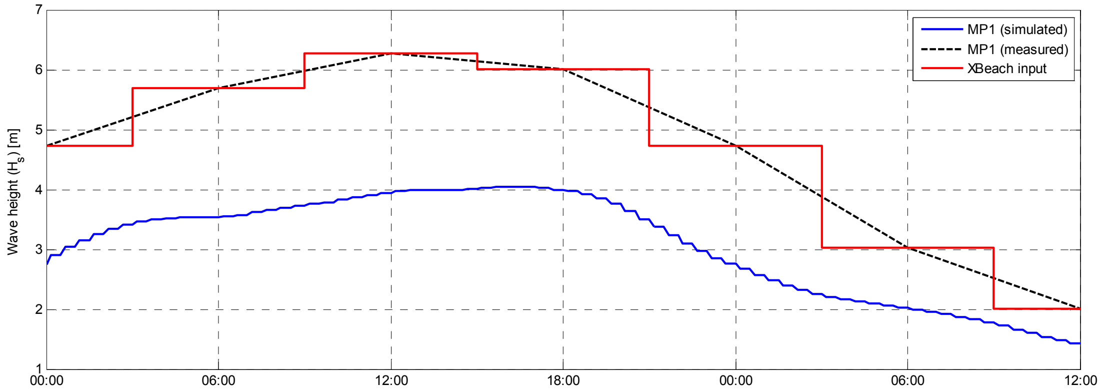
A.7 ’76 storm: Simulated boundary conditions

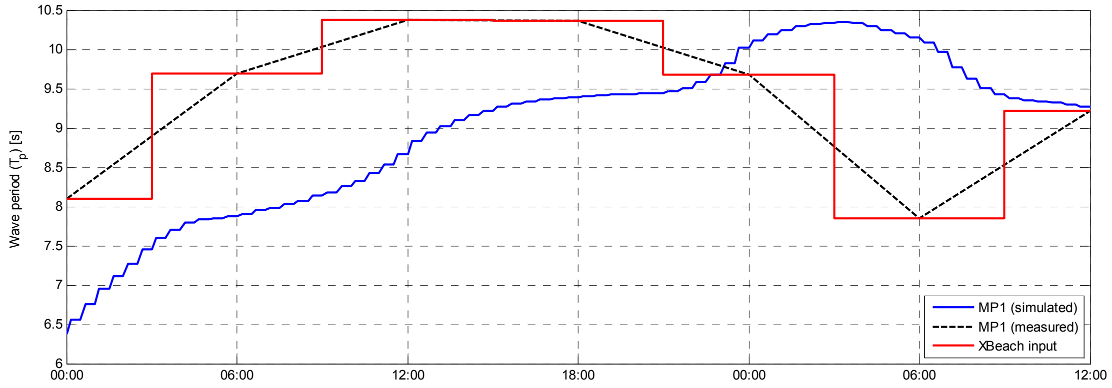
Measured surge vs. simulated surge for Den Helder and Ijmuiden zuidelijk havenhoofd.





Simulated and measured wave conditions for buoy MP1.




Wave period (T_p) [s]
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
00:00
06:00
12:00
18:00
00:00
06:00
12:00
MP1 (simulated)
MP1 (measured)
XBeach input

Deltares

A.8 Model sensitivity (dune height and dune slope)

In chapter 4, the sensitivities of the two models were tested. The results for the parameters, dune height and dune slope, are given below.

Dune height

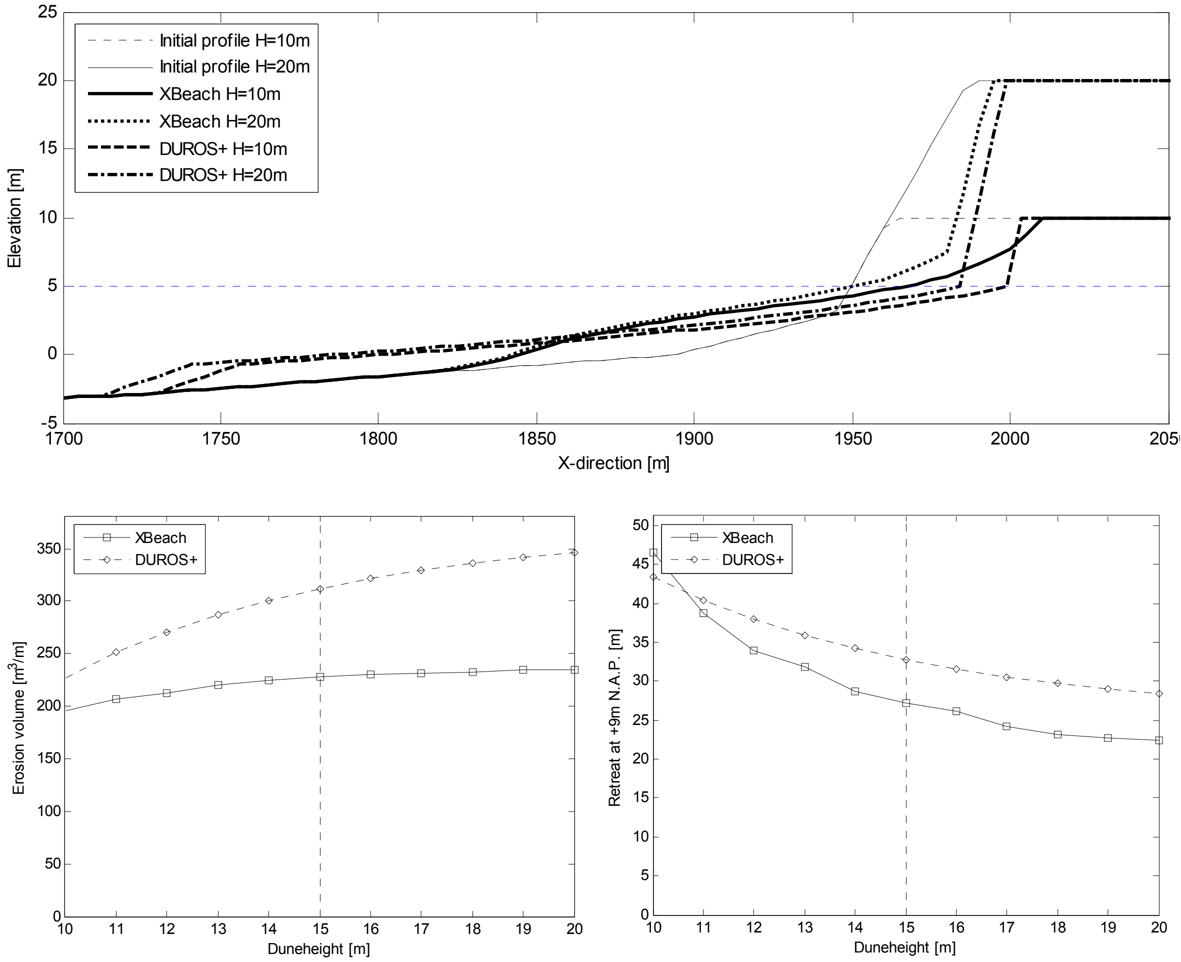


Figure A-8. 1: DUROS- and XBeach-model sensitivity with varying dune height. Upper panel: The predicted profile developments for the lowest dune height (+10m N.A.P.) and the highest dune height (+20m N.A.P.). Lower left panel: The erosion volume above storm surge level. Lower right panel: the dune retreat at +9 m N.A.P. The vertical dotted line indicates the reference value of the dune height.

The DUROS-model shows a non-linear dependency on the dune height. The predicted erosion amount increases with 13% when the dune is heightened with 5 meter. When lowering the dune with 5 meter, the erosion amount decreases with 26%. The shape of the predicted profile is not dependent on the dune height. The dune volume above storm surge level determines the horizontal shift of the profile and results therefore in a smaller dune retreat for higher dunes.
The XBeach-model predicts for the smallest and highest dunes comparable profiles below storm surge level. The difference can be found above storm surge level, the supply side in the model. A lower dune top goes with more dune retreat. The erosion amount increases with 3% when the dune is heightened. When lowering with 5 meters, the dune erosion drops with 14%.

Dune slope

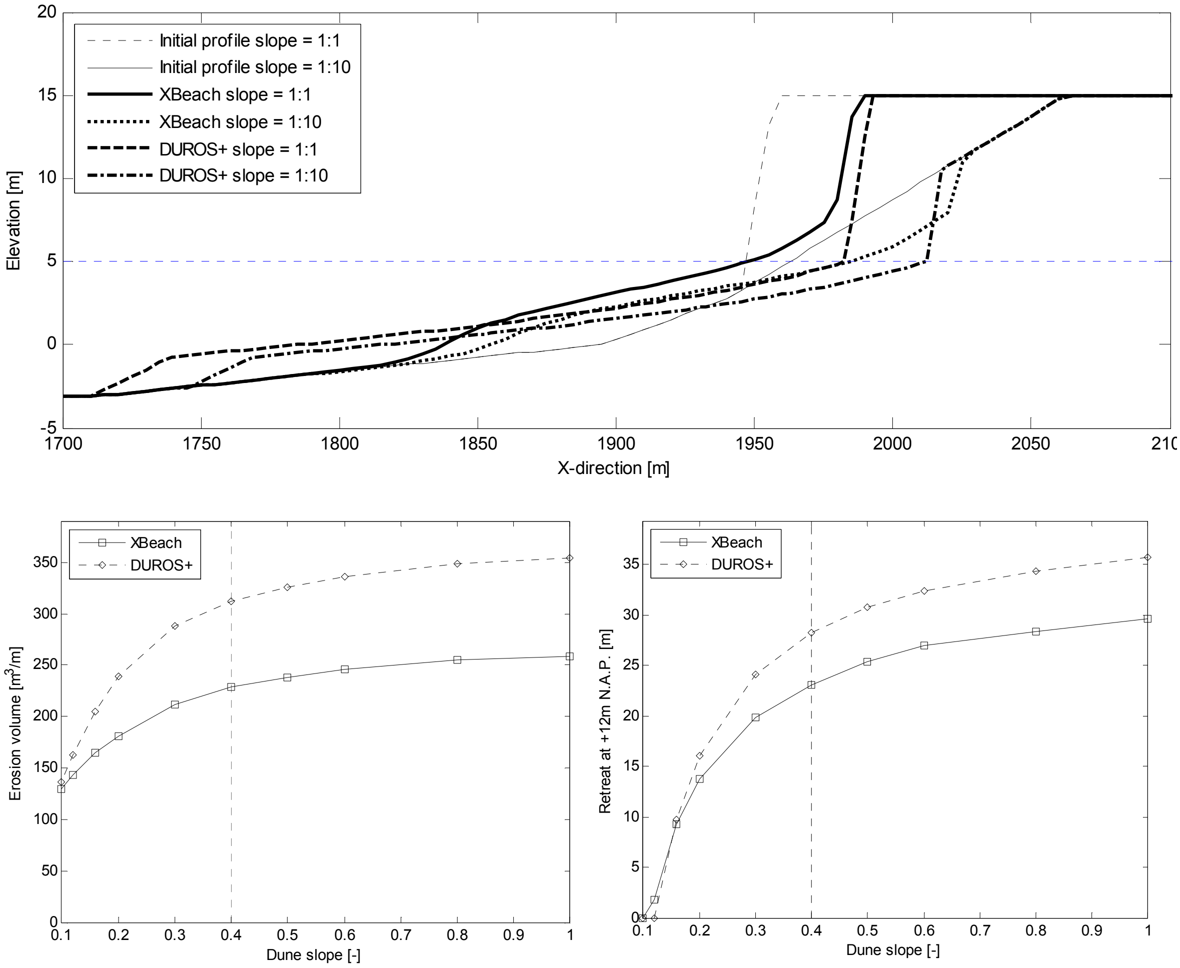


Figure A-8. 2: DUROS- and XBeach-model sensitivity with varying dune slope. Upper panel: The predicted profile developments for the steepest dune slope (1:1) and the most gentle dune slope (1:10). Lower left panel: The erosion volume above storm surge level. Lower right panel: the dune retreat at +12m N.A.P. The vertical dotted lines indicate the reference value of the dune slope.

The profile-shapes in the DUROS-model are not dependent on the dune slope. The dune slope determines the sediment supply above storm surge level, which determines the horizontal shift of the equilibrium profile.

The shape of the predicted profiles for different dune slopes predicted with XBeach is comparable. The seaward extend is dependent on the sediment amount available above storm surge level. The effect of the dune slope to the erosion amount and dune retreat predicted with XBeach is comparable to the effect of the dune slope to the erosion amount and dune retreat predicted with the DUROS-model.

A.8.1 Model sensitivity (DUROS research version and (calibrated) XBeach)

A model sensitivity of the DUROS-model and the (calibrated) XBeach-model was performed once again. The XBeach-model (with adjusted parameters settings) showed similar sensitivity for varying surge level, wave height, wave period and horizontal extension of the (initial) coastal profile. Next, the sensitivity to the dune sediment is analysed more in detail.

Dune sediment
In section 4.4.2 the sensitivity to the dune sediment was analysed. Where the DUROS-model showed to be very sensitive to other sediment sizes, the XBeach-model showed hardly any dependency. Two explanations were proposed to cause the different sensitivities:

- The DUROS sensitivity that is implicitly related to the distortion relation is too high, or
- The sensitivity in the XBeach-model is too low, by
    - o The sensitivity of the supply of sediment from the dune, and/or,
    - o The sensitivity of the demand of sediment from nearshore hydrodynamics.

The supply of sediment from the dune in the present XBeach-model is hardly dependent to the sediment size. In section 3.4, the run-up slope was related to depth scale n_d and fall velocity n_{ws} for distorted models. This relation was also used for relating the *wetslp*-parameter in XBeach to different sediment sizes:

$$n_{wetslp} = \frac{\Delta y}{\Delta x} = n_d^{-0.28} n_{ws}^{0.56} \tag{8.1}$$

In which the fall velocity (w_s) was computed with the Ahrens (2000) relation. The maximum avalanche speed was also expected to be related to the grain size. Since smaller grains have smaller shear stresses their avalanche speed increases (with the same angle of friction). But, as the avalanche speed is also related to the angle of friction (wetslope), the avalanche speed was proposed to be the same for different sediment sizes (relation (4.5)), so:

$$n_{dz\max} = S_f^{1.5} \tag{8.2}$$

In addition, the porosity was expected to be correlated to the grain size. The porosity decreases with smaller grains. This effect was not investigated. In figure 6.10 the new model sensitivity was plotted.

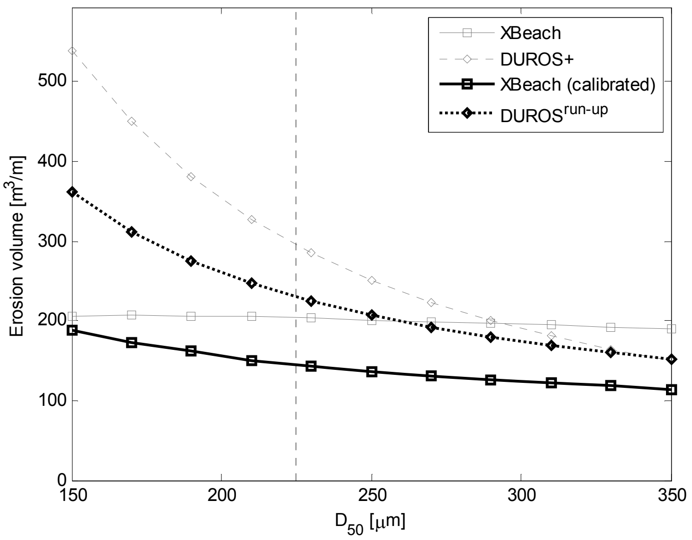


Figure A-8. 3: DUROS research version (from appendix A-1.2) and (calibrated) XBeach-model sensitivity with varying dune sediment. Upper panel: The predicted profile developments for the lowest surge level (3m) and the highest surge level (8m). Lower left panel: The erosion volume above storm surge level. Lower right panel: the dune retreat at +12m N.A.P. The vertical dotted line indicates the reference value of the storm surge level.

In appendix A1-2, a renewed DUROS-model was discussed, with 1) including the wave run-up for dune erosion and 2) an extrapolated (prototype) erosion profile according to the distortion relation. The renewed model is less sensitive to the sediment size, compared to the present DUROS-model. In the new model the run-up height is dependent on the run-up slope. As the run-up slope decreases with smaller grains, the run-up height decreases what results in a smaller sensitivity than the former model.

In the XBeach-model the grain sensitivity increases by relating the *wetslp*-parameter to the grain size (fall velocity).

A.9 Results DUROS research version

In section 5.2.3, a revised DUROS model was introduced. The predicted profiles for the four selected experiments are shown in figure A-9.1.

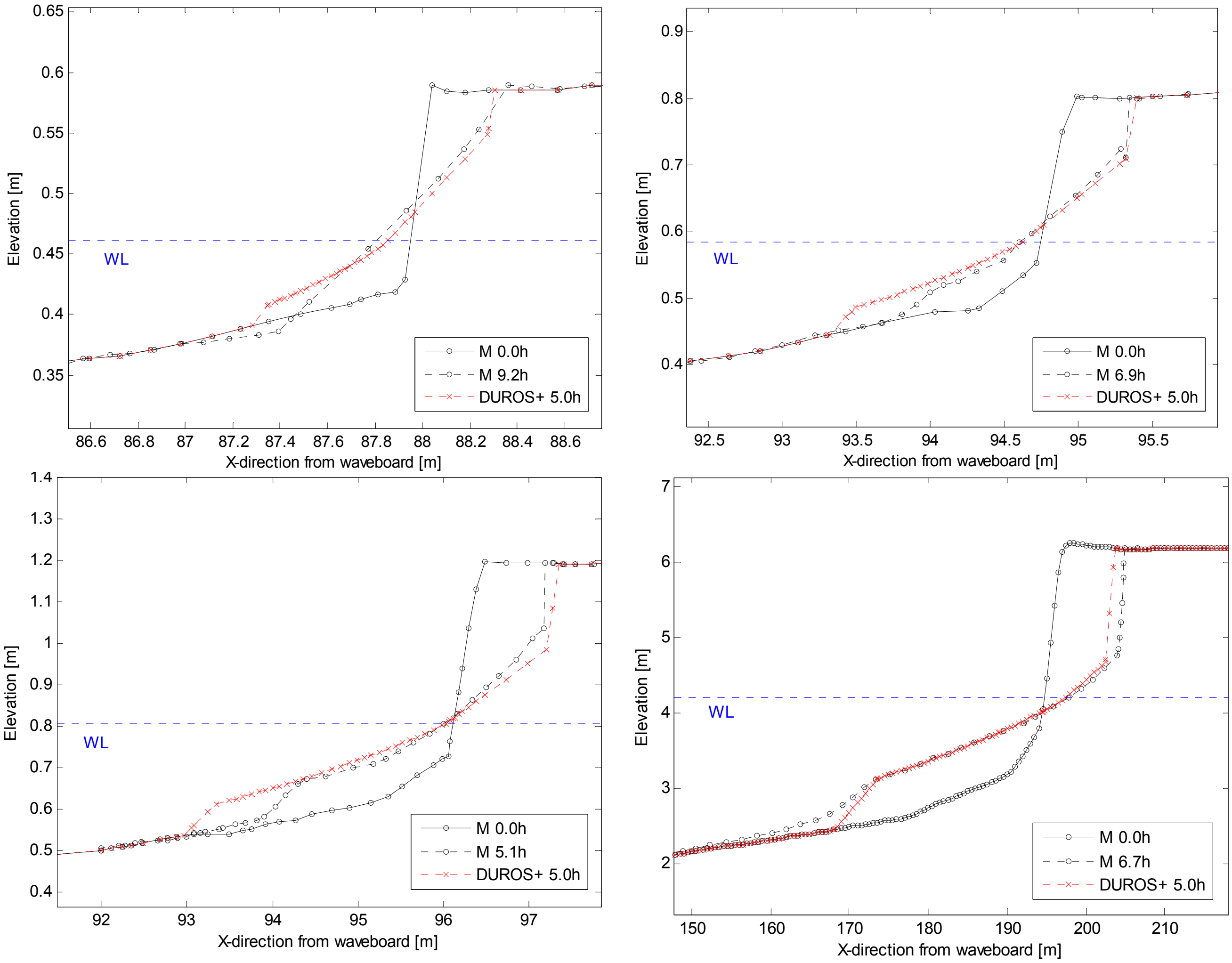


Figure A-9.1: DUROS research version model performance on four depth scales; predicted post storm profiles on laboratory scale. The red dashed line represents the (to laboratory scale converted) DUROS prediction, the black dashed line is the laboratory measurement and the blue dashed line is the water line. Upper left panel: Laboratory experiment test-111 on depth scale 84. Upper right panel: Laboratory experiment test-101 on depth scale 47. Lower left panel: Laboratory experiment test-121 on depth scale 26. Lower right panel: Laboratory experiment test-1 on depth scale 5.