Influence of the wave period in the dune erosion model DUROSTA

Report

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Influence of the wave period in the dune erosion model DUROSTA

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M.sc.Thesis

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Client:	
Title:	Influence of the wave period in the dune erosion model DUROSTA

Abstract:

The dune erosion prediction method presently used in the safety assessment of the Dutch dune coast was developed for situations with wave periods up to 12 seconds. New insights predict that situations with wave periods larger than 12 seconds can be expected. Preliminary analyses of the potential influence of larger wave periods on dune erosion indicate that more erosion occurs for a larger wave period.

The objective of this study is to examine the performance of the process-based model DUROSTA regarding the influence of the wave period, using large scale physical model tests. Results from the physical model tests and DUROSTA simulations are analysed for two wave periods, i.e. peak wave periods of 12 and 18 seconds.

The performance of the different sub models in DUROSTA is examined in more detail, to obtain better insight in the physical processes within in the model. It is concluded that the wave propagation model functions well in the near dune area. DUROSTA underestimates undertow velocities and near dune sediment concentrations significantly. In both the large scale experiments and in the DUROSTA simulations the wave period effect presents itself mainly in higher sediment concentrations, rather than in higher undertow velocities
morphodynamic computations are carried out to study the integral performance of DUROSTA. It is concluded that in general the profile development is well simulated for both wave periods. A clear wave period effect is observed in terms of erosion volumes. After 2.04 hours (5.0 hours in prototype) the relative increase in erosion volume is 25 percent in the physical model tests and 35 percent in DUROSTA computations.

Evaluation of the integral performance of DUROSTA with the conclusions drawn from the analysis of sub models shows that slope effects and the method used for extrapolation of transport over the dry profile, have a large influence on predicting dune erosion with the DUROSTA model.

References:	

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Preface

The present M.Sc Thesis is the final step in completing my study at Delft University of Technology, Faculty of Civil Engineering and Geosciences, section Hydraulic Engineering.

This thesis describes the validation of the dune erosion model DUROSTA using physical model tests from the Delta flume. The validation of the model focuses on the influence of the wave period.

First I would like to thank my graduation committee, Prof. dr. ir. M.J.F. Stive (Delft University of Technology), Dr. ir. J. van de Graaff (Delft University of Technology), Dr. ir. H.J. Steetzel (Alkyon), Dr. J.E.A. Storms (Delft University of Technology) and especially Ir. J.S.M. van Thiel de Vries (Delft University of Technology) and Ir. D.J.R. Walstra (WL | Delft Hydraulics) for their enthusiastic support. Furthermore I would like to thank WL | Delft Hydraulics for the opportunity and facilities they offered me and all my fellow graduate students for the very pleasant time we had at WL | Delft Hydraulics. I really liked all the diners we had and enjoyed the discussions about each others projects.

Finally I would like to show gratitude to all my friends and family for their support and the good times during the last six years. A special thanks goes to Laurens, who really got me through it during the tough times.

Paula van Baaren

Delft, August 2007

Summary

Background

In the Netherlands the safety of the primary water defences is assessed every 5 years. For the safety judgement of the dune coast, a guideline is used which computes the amount of dune erosion during normative conditions. The current guideline (TAW, 1984) does however not take into account the effect of the wave period on the amount of dune erosion.

Some years ago it became clear that the peak wave period during extreme conditions can be significantly larger (up to T_p=18.0 s) than the wave period of 12 seconds which was previously assumed. Small scale physical model tests (Coeveld and De Vroeg, 2004) showed that the amount of dune erosion is clearly depended on the wave period. It is therefore important to account for the influence of a higher wave period in a new/adapted method to predict dune erosion. The time dependent, physical-based cross-shore transport model DUROSTA (Steetzel, 1993) is already able to compute dune erosion taking the wave period into account. However, this model is not validated for large wave periods (T_p>12.0 s).

Recently large-scale physical model tests were carried out in the Delta flume (WL | Delft Hydraulics, 2006). In the model tests dune erosion was simulated under extreme conditions, with different wave periods.

The objective of this study is to examine the performance of the DUROSTA model regarding the influence of the wave period, using the Delta flume test results. Obtained insight can be used in the development of a new/adapted dune erosion prediction method. Results from the physical model tests and DUROSTA simulations were analysed for two wave periods, i.e. peak wave periods of 12 and 18 seconds.

Physical processes in DUROSTA

DUROSTA is a process-based model in which physical processes are represented in several sub models. Some specific results of the ENDEC-model, used for the computation of wave height decay over the cross-shore profile, are used as driving forces for the cross-shore flow and sediment concentration model. From the wave height at a certain point along the profile, the cross-shore sediment transport rate is determined from the product of local velocities and sediment concentrations. In this study first the individual performance of these different sub models is examined in more detail to obtain better insight in the physical processes within in the model.

During the physical model tests an extensive measurement programme was set-up to gain better insight in the physical processes that are important in case of dune erosion under a storm surge. A large dataset was obtained, including the vertical structure of the flow field and sediment concentrations in the near-shore area. This data is used for the analysis of the DUROSTA sub models.

To be able to compare measurements from the physical scale tests directly with results of the DUROSTA sub models, only initial computations are carried out. In every computation the

bottom is updated with the weighted average of measured bottom profiles. In this way the profile in DUROSTA is as close as possible to the actual measured profile in the physical scale model tests and effects due to differences in bathymetry are expected to be negligible.

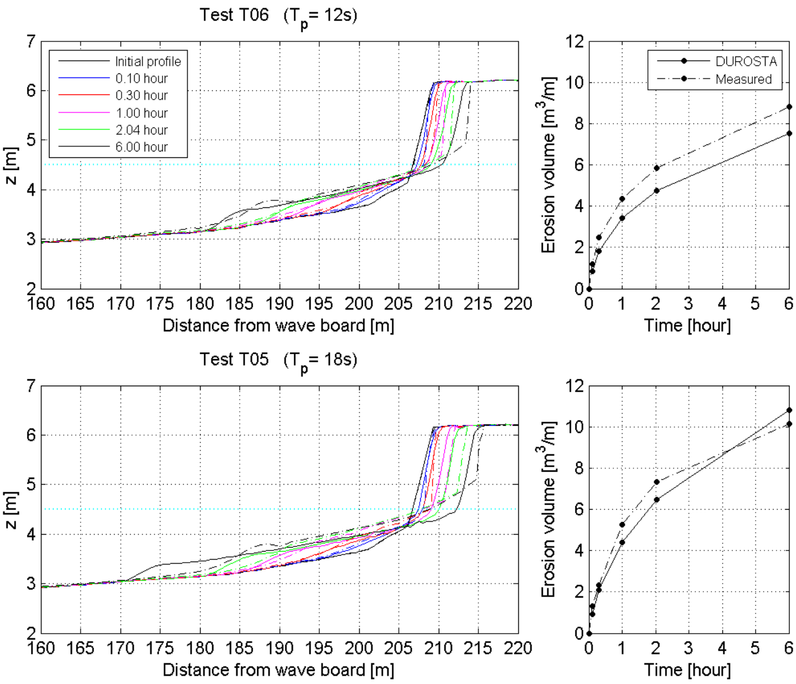
From the analysis of the DUROSTA sub models the following conclusions are drawn:

- The ENDEC-model, used to compute the wave decay of high frequency waves over the profile, functions well for default settings (i.e. $\gamma = 0.85$) in the near dune area. The wave height measurements are slightly overestimated in this area for both wave periods. In the middle of the profile the agreement is less good, since DUROSTA overestimates the wave height here especially for a larger wave period. Both measurements and DUROSTA computations show a larger wave height over the entire profile in case of a larger wave period.
- The undertow velocities are in general underestimated by DUROSTA at deeper water. Especially for a smaller wave period DUROSTA underestimates the measurements significantly up to a factor 2. Computed velocities are slightly higher for a larger wave period. It is therefore concluded that a larger wave period also results in larger undertow velocities in DUROSTA simulations. This tendency is not observed this clearly in the physical model tests.
- DUROSTA underestimates the sediment concentrations significantly, especially close to the dune. Computed sediment concentrations are in general higher for the larger wave period. The trend was also observed in the measurements. During the physical model tests, concentrations increase with a factor 2 in the near dune area, with an increasing wave period.
- For a low wave period, the overall magnitude of the sediment transport is computed well compared to the sediment transport calculated from the measured bed level change. Also trends in time and space are simulated well in this case. For a higher wave period the agreement is less good. The maximum transport is not located at the dune foot but further seaward, indicating erosion in front of the dune foot for initial calculations.
- In both the large scale experiments and in the DUROSTA simulations the wave period effect presents itself mainly in higher sediment concentrations, rather than in higher undertow velocities.

Integral performance of DUROSTA

In order to analyse the performance of the sub models, only initial computations were used. It was therefore not possible simulate in the profile development in time. To gain insight in the integral performance of DUROSTA, full test simulations are carried out and compared to results from the large scale physical model tests.

The profile development over a period of 6.0 hours (model scale) is simulated well by DUROSTA for both wave periods, see figure. The retreat of the dune crest is however underestimated. For a wave period of 12 seconds this results in a consistent underestimation of the erosion volumes. Despite the fact that the dune face retreat is also underestimated for a wave period of 18 seconds, the erosion volumes are predicted rather well. This is explained by the location of the dune foot. DUROSTA simulates the dune foot much lower compared to the measurements, which results in a significant erosion below the water line.



In both the physical scale model tests and DUROSTA simulations a wave period effect is observed, i.e. an increasing amount of dune erosion in case of a larger wave period. After 2.04 hours (5.0 hours in prototype) the relative increase in erosion volume is 25 percent in the physical model tests and 35 percent in DUROSTA computations. After six hours (model scale) the wave period effect has decreased to 15 percent in the measurements. For DUROSTA computations the effect has increased to 43 percent.

Other important processes

Considering that DUROSTA underestimates undertow velocities and near dune sediment concentrations significantly, it is remarkable that profile development and erosion volumes are still quite well simulated. It is therefore concluded that other processes must be present in the model that initiate additional sediment transports. In this respect several components and factors within the DUROSTA model are studied in more detail; i.e. the method of modelling the sediment transport over the dry profile, numerical smoothing, slope correction factor, grid size and location of the dune foot. Based on this analysis the following conclusions are drawn:

Modelling of sediment transport over dry profile

Since the standard computation of sediment transport is not possible for the dry part of the dune, sediment transport in the dry area is determined in a different way. A transition point is chosen and the transport landward from this point is expressed as a fraction of the computed sediment transport in the transition point. To determine this local fraction a reduction factor is applied, depending on the relative bed level and the relative wave run-up.

Regarding the extrapolation of transport over the dry profile, the following conclusions are drawn:

- The influence of different extrapolation methods, i.e. no extrapolation, horizontal extrapolation, vertical extrapolation and the default DUROSTA extrapolation, on the profile development in DUROSTA is relatively small. From this is concluded that the significant run-up is important in modelling the shape of the retreating dune face.

- According to the literature (Steetzel, 1993) the point at a ¼ wavelength seaward of the waterline is used as the transition point between the wet and dry profile. However, in the DUROSTA code the last wet computing point is used as the start of extrapolation of sediment transport over the dry profile. The ¼ wavelength is used in the calculation of the reduction factor and the determination of the relative wave run-up.
- DUROSTA is very sensitive to the distance of a ¼ wavelength. For a larger fraction of the wavelength the dune face gets steeper. For a smaller fraction, an irregular shape of the dune face is computed.
- The significant run-up in DUROSTA has limited influence on the amount of dune erosion. This is remarkable since the run-up was assumed to be the governing physical parameter in the calculation of the reduction factor.
- In DUROSTA the method of extrapolation of transport over the dry profile forces the dune foot to be located near the water line. However during the physical model tests the dune foot moves up to above the water level, especially for a peak wave period of 18 seconds. DUROSTA simulations give therefore unrealistic results regarding the location of the dune foot for simulations with a wave period of 18 seconds.

Numerical smoothing

- The influence of the numerical smoothing factor on the DUROSTA simulations in this study is negligible.

Bed slope effects

Two calibration factors are available in DUROSTA to take slope effects on sediment transports into account, i.e. K_{sl} and K_{sw}. It is noted that K_{sw} is defined different in the DUROSTA code than in the literature (Steetzel, 1993). Here it was described as an additional numerical smoothing factor, whereas in the DUROSTA code K_{sw} is defined as an additional slope effect.

Regarding the bed slope effects, the following conclusion is drawn:

- The influence of bed slope effects on DUROSTA simulations in this study is very large. It was found that 60 percent of the dune erosion is initiated by bed slope effects.

Grid size

- In DUROSTA the grid size mainly influences the shape of the upper part of the dune face. In case of a small grid size the predicted dune face gets steeper and less dune erosion is computed. For a larger grid size the effect is the other way around.

Sensitivity analysis

A sensitivity analysis is performed to gain better insight in the influence of the main physical parameters on the computations. The analysis focuses on the sensitivity of the different parameters in relation to the wave period. In this way it is studied how the wave period effect on dune erosion is influenced by certain other physical parameters, i.e. water level, wave height, breaker index and grain size. Additionally the influence of the initial profile is examined. From the sensitivity analysis the following conclusions are drawn:

Water level

- In DUROSTA the amount of dune erosion increases fast with an increasing water level.
- The relative wave period effect is not affected by water level variations.

Wave height

- In DUROSTA the wave height is a very important parameter in predicting dune erosion. The wave period effect is highly influenced by the wave height. For a larger wave height the wave period effect increases significantly.

Breaker index

- DUROSTA is very sensitive to the breaker index. This is also expected since the breaker index was one of the main calibration parameters and directly determines the wave energy dissipation due to wave breaking and by that wave transformation over the profile. Additionally, the breaker index is also included in the sediment concentration formulation.
- Applying the breaker index according the Battjes and Stive (1985) in DUROSTA simulations, results in an inverse wave period effect for prototype wave periods larger than 11 seconds. In this case erosion volumes decrease with an increasing wave period, which is in contrast with the measurements.
- Application of the breaker index according to Ruessink *et al*. (2003) in DUROSTA simulations results in a significant underestimation of the amount of erosion.

Grain size

- In DUROSTA the amount of dune erosion increases with a decreasing grain size. The wave period effect gets larger for a smaller grain size.

Initial profile

- When measured erosion profiles from the physical model tests are applied in DUROSTA simulations as initial profile, the influence on the end profile (6 hours) is very small.

Simulations on prototype scale

In this study a reference profile (which is considered characteristic for the Dutch dune coast) was used for simulating dune erosion on scale of the physical model tests. The performance of DUROSTA on a prototype reference profile is assessed as well to determine whether scale effects play a role in the simulations. Additionally, simulations with real dune profiles from the Dutch coast have been carried out. It is examined whether the wave period effect predicted for the reference profile agrees with the wave period effect computed for real dune profiles. The erosion profiles on model scale and prototype scale are both compared to the DUROS+ model for wave periods of 12 and 18 seconds.

From simulations on prototype scale the following conclusions are drawn:

- For simulations with the reference profile on prototype scale, the wave period effect computed by DUROSTA is approximately 40 percent. This percentage was 35 for simulations on model scale. It is therefore concluded that scale effects have a small influence in the DUROSTA simulations regarding the wave period effect.

- The DUROS+ model overestimates the computed erosion volumes by DUROSTA significantly for wave periods of 12 and 18 seconds. For simulations on model scale this overestimation is a factor 2.6 and 2.2 for respectively a wave period of 12 and 18 seconds. For simulations on prototype scale this respectively a factor 1.9 and 1.7.
- There is a large difference between the overestimation of the DUROSTA results by DUROS+ on model scale and prototype scale. This may be explained by the fact that scale relations are included different in DUROSTA than in the empirical models.
- DUROSTA simulates a significant variability of the wave period effect for different locations along the Dutch coast. The mean wave period effect is 46 percent for measured dune profile along the Dutch coast, which is slightly larger than the 40 percent that was found for the simulations with the reference profile.

Contents

Appendices

1 Introduction

1.1 Background

During normal conditions the beach profile of a sandy coast is considered to be in a more or less dynamic equilibrium. During storm surges this equilibrium state is disturbed since dunes are exposed to much higher water levels and more severe wave attack. Under these circumstances large amounts of sediment erode from the dune face and are deposited in front of the dune, on the beach and foreshore. In this way the cross-shore profile is forced into a new equilibrium that fits better to the storm surge conditions. It is however not expected that a real equilibrium profile will develop during storm conditions because of the limited duration of a storm. The general beach profile before and after a storm is shown in Figure 1.1.

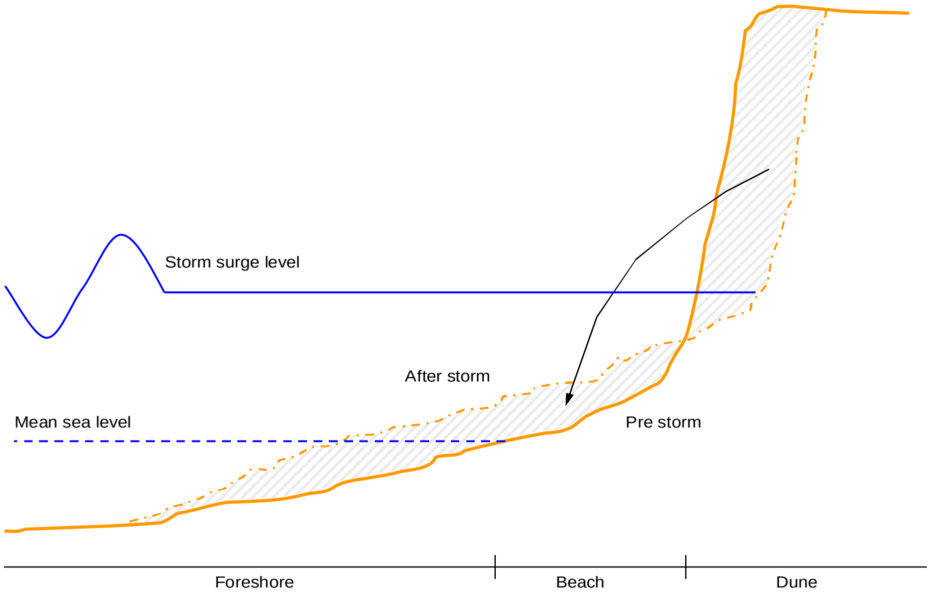


Figure 1.1 Dune erosion during storm surge

Dune erosion during a storm surge leads to a fast decreasing width of the dune in a relatively small period of time. After the storm, the profile will gradually return to the pre-storm equilibrium situation. During these normal conditions the wind and smaller waves transport the eroded material back to the upper part of the beach profile. Dune erosion is in this way a reversible process and is therefore in principle not a problem but a part of the natural dynamics of a beach. However, problems do occur when the erosion of the dune becomes so large that buildings on the dune are damaged or when even a breach occurs, causing inundation of the hinterland. To obtain insight in these safety problems, a quantification method is required that gives reliable predictions of the amount of dune erosion during severe storm surge conditions.

In the Netherlands the safety of the primary water defences is assessed every 5 years for a water level which has a probability of exceedence of 1/10,000 per year. Guidelines used for the safety assessment of the dunes are described in the Guide on Dune Erosion (in Dutch: ‘Leidraad Duinafslag’, TAW, 1984). In these guidelines the under water bed profile is calculated for normative hydraulic conditions with a parabolic erosion profile. The significant wave height at deep water, the water level and a characteristic diameter of the dune sand (related to fall velocity) are parameters used to calculate the shape of the erosion profile. However, the dune erosion profile is expected to depend also on other variables that are not included in this present method, such as the wave period.

Some years ago it became clear that the peak wave period during storm surges can be significantly larger (T_p>12.0 s) than previously assumed (see also Alkyon, 2002, Rijkswaterstaat 1996 & 2002 and WL | Delft Hydraulics, 2003). The present safety assessment method is only verified for the smaller wave periods (T_p<12.0 s). Small-scale dune erosion tests (Coeveld and De Vroeg, 2004) showed a larger volume of dune erosion with an increasing wave period. It is therefore important to obtain more detailed knowledge on the influence of the wave period on dune erosion, to account for this influence in an adapted method to calculate dune erosion.

1.2 Problem analysis

The ‘Directoraat-Generaal Rijkswaterstaat’, RIKZ accepted a proposal of WL | Delft Hydraulics (ref: MCI-10835/H4357/MvG, dated May 20th, 2005) to carry out a project in which a new safety assessment method is developed. On a short term it was required to take the effects of the wave period into account in the existing method used to calculate dune erosion (Vellinga, 1986). At the time of writing the extended model became available and is described by Van Gent *et al.* (2007). To be able to validate this new method large scale model tests were carried out in the Delta flume. In these model tests dune erosion under extreme conditions was simulated with different wave periods.

In the near future an appropriate safety assessment tool is required for more complex coastal systems with dunes. It is in this respect useful to study the performance of the existing dune erosion models. The time dependent, physical-based cross-shore transport model DUROSTA (Steetzel, 1993) is able to compute dune erosion taking the wave period into account. However, this model is not validated for large wave periods (T_p>12.0 s). Comparison of the Delta flume test results with corresponding DUROSTA computations will give insight in the performance of the model concerning the wave period dependency. This knowledge can be used in the development of a new dune erosion prediction method. An additional reason why it is interesting to use such a model is that it is also able to simulate the temporary position of the shoreline (by relating the dune face erosion to the momentary transport capacity of near shore flow). In the current safety assessment method the time dependency in the dune erosion process during a storm surge is not included.

1.3 Objective

Based on the previous problem analysis the following objective has been formulated:

validation of the DUROSTA model, taking into account the influence of the wave period

1.4 Research approach

The DUROSTA model is a process-based dune erosion model. In such a model dune erosion is computed on the basis of physical processes. The general idea is that all physical processes, which are important in modelling dune erosion during a storm surge, are included in the model. In DUROSTA these physical processes are represented by the different sub models. It is expected that, if the individual performance of these different sub models is good, the dune erosion model is able to give a reliable prediction of dune erosion during a storm surge. In this study the performance of the sub models in DUROSTA and the integral performance of DUROSTA are examined in detail. The analysis has focussed on the influence of the wave period in the model.

First a detailed literature review has been performed to gain a better view on the aspects which are important in modelling dune erosion under a storm surge and which components are applied in dune erosion models. Based on the analysis a detailed description of the most important sub models in DUROSTA is given in Chapter 2.

Validation of the model is carried out using data from large scale model tests performed in the Delta flume. An analysis of the large scale physical model tests is executed in Chapter 3, to select useful data for validation of the DUROSTA model as a whole and for validation of the different sub models. Subsequently a detailed data analysis is performed to study the physical processes which determine dune erosion during a storm surge. Also the impact of the wave period on dune erosion is studied.

Based on the detailed data analysis from Chapter 3, the individual performance of DUROSTA sub models and the integral performance of DUROSTA are assessed in respectively Chapter 4 and Chapter 5. An important part of this analysis is to study the performance of the sub models regarding the influence of the wave period.

In Chapter 6 the performance of DUROSTA on prototype scale is assessed, to determine whether scale effects may play a role in the simulations. Since in this study a reference profile of the Dutch coast was used for simulating dune erosion, the influence of simulating with real dune profiles from the Dutch coast is studied as well. The erosion profiles on model scale and prototype scale are both compared to the existing empirical model (Vellinga, 1986) and the extended empirical model (Van Gent *et al.*, 2007) to predict dune erosion.

In Chapter 7 conclusions from this study are summarised and recommendations for further research are proposed.

2 Description of DUROSTA

In this chapter a brief outline of the DUROSTA model is presented. For a more extensive description of the model reference is made to Steetzel (1993) and Steetzel (1994).

2.1 DUROSTA

DUROSTA (also known as UNIBEST-DE) is a process-based numerical dune erosion model. Instead of a description of a final erosion profile (current safety assessment method) DUROSTA is able to simulate the development of the erosion profile in time from the instantaneous cross-shore transports. It is also possible to include effects of longshore transport gradients in the model, in this study however these formulations are not used.
The basic principle of the model is that the cross-shore sediment transport rate is computed from the product of local velocities and sediment concentrations according to the following equation:

$$S(x)=\frac{1}{nT}\int_{t=0}^{nT}\int_{z=0}^{\eta(x,t)} u(x,z,t)\,C(x,z,t)\,dz\,dt \tag{2.1}$$

in which:

S	(x-component of the) net transport	[m^3/m/s]
u	(x-component of the) cross-shore velocity	[m/s]
C	sediment concentration	[-]
x	horizontal position	[m]
t	time	[s]
T	wave period	[s]
z	vertical coordinate with respect to bed	[m]
η	instantaneous water level	[m]
n	sufficiently high number of waves	[-]

To be able to use this equation knowledge of variations in time and space of the vertical distribution of the velocities and concentrations is required. Because of the lack of knowledge regarding these fluctuations a simplification was made. In the mathematical description of the cross-shore sediment transport the so-called wave related transport is neglected and only the current related transport is taken into account. In the case of dune erosion during a storm surge, this assumption is acceptable (inside the breaker zone). During these extreme conditions the amount of sediments in the vertical is very large and the transport depends mainly on the average velocities resulting from the relatively strong undertow. Outside the breaker zone this assumption is not valid because of the increasing correlation between the fluctuating water movement and sediment concentration. A second simplification is that DUROSTA only takes suspended transport into account and neglects bottom transport. Because the bottom transport is often landward directed, this assumption may imply an underestimation of the landward directed sediment transport. However for calculations in the breaker zone and short time scales this neglect is considered acceptable.

The simplified DUROSTA model (without longshore transport) can be divided into five sub models. The scheme in Figure 2.1 shows how these sub models interact with each other.

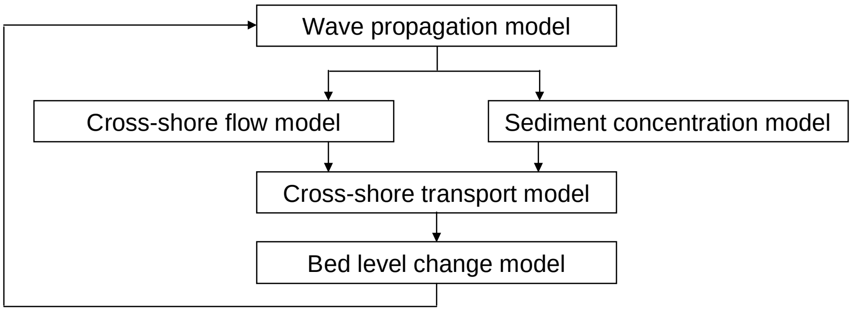


Figure 2.1 Overview of DUROSTA sub-models (Den Heijer, 2005)

In one time step DUROSTA computes at first the local wave height according to wave height decay model ENDEC (Battjes and Janssen, 1978) at many locations along the profile. From the local wave height the cross-shore flow and the sediment concentrations are computed in the cross-shore profile. Subsequently the depth-integrated product of the time-averaged velocities and time-averaged concentrations results in local cross-shore transport rates. Finally bottom changes are computed using a sediment mass balance equation, resulting in a new profile which is used in the next time step. The time step used in DUROSTA is variable and depends on the magnitude of bottom change.

In the following paragraphs these five sub models are described briefly. The descriptions are mainly obtained from Steetzel (1993) and Den Heijer (2005).

2.2 Wave propagation model

For each computational time step the local hydraulic conditions across the momentary profile are computed using the ENDEC model (Battjes and Janssen, 1978), starting with the seaward boundary conditions.

2.2.1 ENDEC model

The two basic equations that compute the hydraulic conditions are the wave energy balance and the cross-shore momentum equation. The equations describe the wave height decay taking into account the wave induced cross-shore water level set-up. The first differential equation, the wave energy balance for perpendicular incoming waves, is described by:

$$\frac{dEc_g}{dx} + D_b + D_f = 0 \tag{2.2}$$

in which:

Ec_g	energy flux	[W/m]
E	wave energy per unit area	[J/m^2]
c_g	wave group velocity	[m/s]
D_b	wave energy dissipation rate due to breaking	[J/m^2/s]
D_f	wave energy dissipation rate due to bottom friction	[J/m^2/s]
x	horizontal cross-shore coordinate	[m]

The wave energy is given by:

$$E = \frac{1}{8}\rho g H_{rms}^2 \tag{2.3}$$

in which:

ρ	mass density of water	[kg/m^3]
g	gravitational constant	[m/s^2]
H_{rms}	root mean square wave height	[m]

The wave energy dissipation rate due to breaking is described by:

$$D_b = \frac{1}{4}\rho g \alpha Q_b \left(\omega / 2\pi\right) H_m^2 \tag{2.4}$$

in which:

α	dissipation coeffient	[-]
Q_b	fraction of breaking waves	[-]
ω	angular frequency *(=2π/T)*	[rad/s]
T	wave period	[s]
H_m	maximum breaking wave height	[m]

It is assumed that in deep water the maximum wave height is limited by the maximum wave steepness. Waves which are higher than H_m break and smaller non-broken waves are Rayleigh distributed. The maximum wave height is described by:

$$H_m = \left(\frac{0.88}{k}\right)\tanh\left(\frac{\gamma k d}{0.88}\right) \tag{2.5}$$

in which:

k	wave number	[m^{-1}]
γ	breaker index	[-]
d	water depth	[m]

The local fraction of breaking waves is described by:

$$\frac{1-Q_b}{-\ln Q_b} = \left(\frac{H_{rms}}{H_m}\right)^2 \tag{2.6}$$

The wave energy dissipation rate due to bottom friction is described by:

$$D_f = \frac{1}{8}\rho f_w \pi^{-\frac{1}{2}} \left(\omega H_{rms} / \sinh\left(kd\right)\right)^3 \tag{2.7}$$

in which:

f_w	bottom friction factor	[-]

The cross-shore time integrated momentum equation, accounts for the change in mean water level due to the radiation stress effect and is described by:

$$\frac{dS_{xx}}{dx} + \rho g\left(d + \overline{\eta}\right)\frac{d\overline{\eta}}{dx} = 0 \tag{2.8}$$

in which:

S_{xx}	radiation stress in x-direction through x-plane	[J/m^2=N/m]
$\overline{\eta}$	(time averaged) mean water level elevation above the mean water level *d* due to wave set-up or set-down	[m]

The radiation stress is described by:

$$S_{xx} = \left(2n - \frac{1}{2}\right)E \tag{2.9}$$

in which:

n	ratio of wave group and phase velocity (c_g/c)	[-]

More information on these basic equations and the ENDEC-model is given in Stive and Dingemans (1984) and Battjes and Stive (1985).

2.2.2 Turbulence model

Since initially the start of the wave-set up was predicted too far seaward, a turbulence model was applied. Instead of wave energy immediately being dissipated after the breakpoint, wave energy is converted into turbulent kinetic energy first. In this way the dissipation process is delayed, which moves the region of wave set-up in shoreward direction.
In the dissipation term D_b an additional differential equation is included to make a distinction between the dissipation source term in the wave energy balance equation due to breaking D_b and the dissipation of turbulent kinetic energy D_t.

$$\frac{dP_t}{dx} + D_t = D_b \tag{2.10}$$

in which:

P_t	turbulent energy flux	[J/s/m]
D_t	turbulent energy dissipation rate	[W/m^2]

The turbulent dissipation D_t is described by (Launder and Spalding, 1972):

$$D_t = \rho \overline{K}^{\frac{3}{2}} \tag{2.11}$$

in which:

$\overline{K}$	depth-averaged, turbulent energy per unit of mass	[J/kg]

The mean turbulent energy flux P_t is computed from:

$$\frac{dP_t}{dx} = \rho \frac{d}{dx}\left(cd\overline{K}\right) \tag{2.12}$$

in which:

c	wave celerity	[m/s]

A combination of former equations and successive elaboration in an iterative computational procedure yields a cross-shore distribution of the turbulent dissipation term. More details about this can be found in Roelvink and Stive (1989).

2.3 Cross-shore flow model

The description of the time-averaged velocity profile below the mean wave trough level is based on the vertical distribution of the time averaged shear stress. The formulation of the time averaged velocity profile below the wave trough consists of three contributions; a uniform, a linear and a logarithmical part, and is described by:

$$u(z) = u_0 + K_{lin} z + K_{\log} \ln\left(1 + \frac{\mu z}{\varepsilon_0}\right) \tag{2.13}$$

in which:

z	vertical coordinate	[m]
u_0	(virtual) velocity at reference level near the bed	[m/s]
K_{lin}	constant related to linear contribution to $u(z)$	[s^{-1}]
K_{log}	constant related to logarithmic contribution to $u(z)$	[m/s]
μ	vertical mixing gradient $(\Delta\varepsilon/\Delta z)$	[m/s]
ε_0	reference mixing coefficient at level $z=0$	[m^2/s]

The profile constants K_{lin} and K_{log} are defined by:

$$K_{lin} = \frac{\alpha}{\mu} \tag{2.14}$$

$$K_{\log} = \frac{1}{\mu}\left(\beta - \frac{\alpha}{\mu}\varepsilon_0\right) \tag{2.15}$$

in which:

α	positive shear stress gradient ($(d\bar{\tau}/dz)/\rho$)	[m/s^2]
β	constant (τ_0/ρ)	[m^2/s^2]

The reference mixing coefficient ε_0 and the mixing gradient μ are described by:

$$\varepsilon_0 = K_\varepsilon D_{50} u_{rms} \gamma \tag{2.16}$$

$$\mu = K_\mu c / \gamma \tag{2.17}$$

in which:

K_ε	constant	[-]
D_{50}	geometric mean sediment diameter	[m]
u_{rms}	root mean square orbital velocity	[m/s]
γ	breaker index	[-]
K_μ	constant	[-]

It is assumed that the wave induced mass transport towards the coast is concentrated to a small zone above the level of the mean wave troughs. The mass flux *m* is directed to the shore and is described by a wave related and roller related part as follows:

$$m = \frac{E}{c} + P_{br} K_r \rho \frac{H_{rms}^2}{T_p} \tag{2.18}$$

in which:

m	landward directed mass flux above the mean trough	[kg/m/s]
P_{br}	portion of breaking waves	[-]
K_r	dimensionless quotient of roller area and H_{rms}^2	[-]
T_p	peak wave period	[s]

This transport of mass in the upper part of the vertical is compensated by a seaward directed secondary current in the lower vertical, see also Figure 2.2. In storm situations this vertical pattern is regarded as the most dominating pattern for offshore transport (see e.g. Short, 1978).

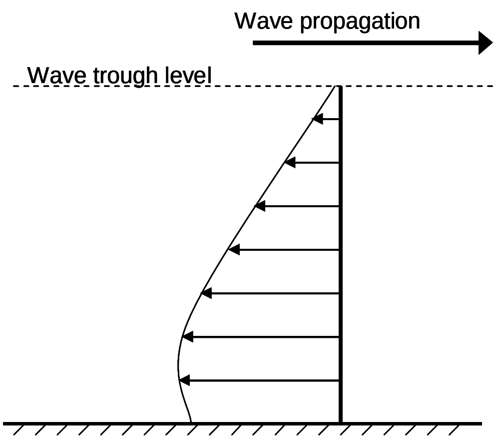


Figure 2.2 Secondary flow profile

The final expression for the velocity profile below the wave trough level is derived from application of this continuity condition:

$$-\frac{m}{\rho} = u_0 d_t + \frac{1}{2} K_{lin} d_t^2 + K_{\log} I_0 \tag{2.19}$$

in which:

d_t	water depth below mean wave trough level	[m]
I_0	constant	[m]

in which constant I_0 is described by:

$$I_0 = \frac{\varepsilon_0}{\mu} \left[\left(1 + \frac{\mu d_t}{\varepsilon_0} \right) \left[\ln\left(1 + \frac{\mu d_t}{\varepsilon_0} \right) - 1 \right] + 1 \right] \tag{2.20}$$

2.4 Sediment concentration model

In DUROSTA the bottom transport is neglected and only the suspended transport is taken into account to compute cross-shore transport. This assumption is allowed because during storms, most of the sediment transport takes place as suspended load. The vertical distribution of the time-averaged sediment concentration is described by:

$$C(z) = C_0\left[1+\frac{\mu z}{\varepsilon_0}\right]^{(-w_s/\mu)} \tag{2.21}$$

in which:

C_0	reference sediment concentration (at z=0 m)	[kg/m^3]
w_s	fall velocity of sediment with grain size $D=D_{50}$	[m/s]

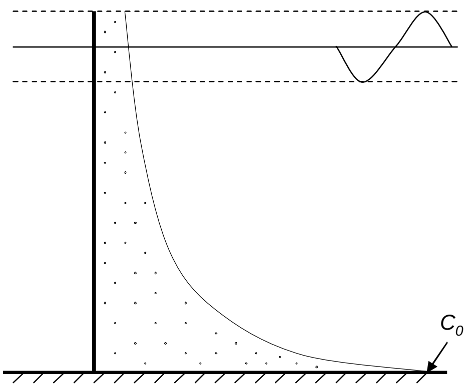


Figure 2.3 Sediment concentration profile

The mixing parameters ε_0 and μ and the fall velocity of the sediment w_s determine the shape of the concentration profile. Its overall magnitude is controlled by the reference concentration at the bed, C_0.

For non-breaking waves the sediment concentration is often related to the near-bottom velocity and accompanying bottom shear stresses. For breaking waves however, the amount of suspension and thus the reference concentration is probably also related to the turbulence level generated from the breaking waves. Due to the wave breaking process a certain amount of turbulent kinetic energy is released from the upper zone. Depending on the way of breaking a specific fraction of this energy reaches the bottom and causes an increase in the near bottom sediment suspension quantity. In DUROSTA the amount of suspension is related to both the intensity of breaking and the way of breaking according to:

$$C_0 = \rho_s K_c F_D \left(\frac{\rho}{\tau_{cr}}\right)^{\frac{3}{2}} F_k^{\frac{3}{2}} \left(\frac{D_t}{\rho}\right) \tag{2.22}$$

in which:

ρ_s	mass density of sediment	[kg/m^3]
K_c	constant	[-]
F_d	function related to the sediment diameter	[-]

$$F_D = \left(\frac{0.000225}{D_{50}} \right)^{\alpha_D} \tag{2.23}$$

α_D	constant	[-]
τ_{cr}	critical shear stress	[N/m^2]

$$\tau_{cr} = \Theta_{cr} \left(\rho_s - \rho \right) g D_{50} \tag{2.24}$$

Θ_{cr}	critical Shields parameter	[-]
F_k	function which describes the effect of the way waves break	[-]

$$F_k = \left[\alpha_k \gamma \left(\exp\left(\frac{1}{\alpha_k \gamma} \right) - 1 \right) \right]^{-1} \tag{2.25}$$

α_k	constant	[-]

2.5 Cross-shore transport model

As discussed previously, the cross-shore sediment transport can be calculated from a depth integrated product of the time averaged velocity profile and the time averaged sediment concentration profile. Due to the definition of the secondary current the sediment transport has to be divided into two components; a transport below the mean wave trough level and a transport above this level:

$$S = S_l + S_u \tag{2.26}$$

in which:

S	(time averaged) depth integrated sediment transport per unit width	[kg/s/m]
S_l	sediment transport below wave trough level	[kg/s/m]
S_u	sediment transport above wave trough level	[kg/s/m]

The lower contribution to the sediment transport S_l is in the offshore direction and is described by:

$$S_l = C_0 \left(u_0 I_1 + K_{lin} I_2 + K_{\log} I_3 \right) \tag{2.27}$$

in which the parameters I_1 [m], I_2 [m^2] and I_3 [m] are given by:

$$I_1 = \frac{\varepsilon_0}{\mu} \frac{1}{K_1} \left(K_2^{K_1} - 1 \right) \tag{2.28}$$

$$I_2 = \frac{\varepsilon_0}{\mu} \frac{1}{K_1} \left(K_2^{K_1} \left(d_t - \frac{\varepsilon_0}{\mu} \frac{K_2}{K_1 - 1} \right) + \frac{\varepsilon_0}{\mu} \frac{1}{K_1 + 1} \right) \tag{2.29}$$

$$I_3 = \frac{\varepsilon_0}{\mu} \frac{1}{(K_1)^2} \left(K_2^{K_1} \left(K_1 \ln(K_2) - 1 \right) + 1 \right) \tag{2.30}$$

in which two additional, dimensionless constants K_1 and K_2 are defined as:

$$K_1 = 1 - w_s / \mu \tag{2.31}$$

$$K_2 = 1 + (\mu / \varepsilon_0) d_t \tag{2.32}$$

The landward transport above the mean trough level is described by the product of the time-averaged concentration at the mean water level and the net amount of shoreward moving water (e.g. mass flux). In breaking waves with sediment suspended over the whole water depth this on-shore directed transport can not be neglected and can be described by:

$$\begin{aligned} S_u &\approx C_0 f_c(d) \frac{m}{\rho} \\ &= -C_0 f_c(d) \left[u_0 d_t + \frac{1}{2} K_{lin} d_t^2 + K_{\log} I_0 \right] \end{aligned} \tag{2.33}$$

in which the relative concentration at the mean water level is described by:

$$f_c(d) = \left(1 + \frac{\mu d}{\varepsilon_0} \right)^{\left(\frac{w_s}{\mu} \right)} \tag{2.34}$$

The total net sediment transport can now be written as:

$$S = C_0 \left[u_0 \left(I_1 - f_c(d) d_t \right) + K_{lin} \left(I_2 - f_c(d) \frac{1}{2} d_t^2 \right) + K_{\log} \left(I_3 - f_c(d) I_0 \right) \right] \tag{2.35}$$

2.5.1 Additional calibration factors

According to Steetzel (1993) three additional transport correction factors are applied for calibration of the model, namely:

- An overall correction factor on the transport rate K_{cor} to correct for inadequacy of the transport model.
- A correction factor K_{sl} to deal with the effects of the bottom slope
- A beach/swash factor K_{sw} to cope with the effects of numerical instability in the swash zone

The transport rate computed from the expressions in the previous paragraph is multiplied with a transport correction factor K_{cor}. This was done to enable tuning of the model using observed development of erosion profiles. The default value of the transport correction factor is 1.6.

A slope correction factor is used to include bed-slope effects into the sediment transport over the wet profile. In order to account for the additional impact of the bottom slope the following correction is applied:

$$S_x^{'}(i) = \left[1 + K_{sl}\left(\frac{\Delta z_b}{\Delta x}\right)\right] S_x(\text{i}) \Bigg|_{i=1}^{i=last\ wet\ gridcel} \tag{2.36}$$

in which:

K_{sl}	slope correction factor (default value=4.0)	[-]

In the transition zone between shallow water and dune face, the mathematical model tends to generate unacceptable bottom irregularities. Steetzel (1993) and Steetzel (1994) both state that this effect is handled by applying additional numerical smoothing in the swash zone (see also Paragraph 2.7) as follows:

$$\gamma^{'} = K_{sw}\gamma \tag{2.37}$$

in which:

K_{sw}	swash factor (default value=2.0)	[-]
γ	numerical smoothing factor	[-]

In the DUROSTA version used for this study a swash factor is indeed applied but different than is described in Steetzel (1993 and 1994). From the DUROSTA model code can be concluded that again a slope effect is included as in Equation (2.36). However, this time two additional factors are included, i.e K_{sw} and a (local) wave height over depth ratio. A difference is that the variable K_{sl} is replaced by the default value of K_{sl}=4.0. Finally the sediment transport over the dry profile is described by:

$$S_x^{''}(i) = \left[1 + 4 * K_{sw}\frac{H_{rms}}{h}\left(\frac{\Delta z_b}{\Delta x}\right)\right] S_x^{'}(\text{i}) \Bigg|_{i=2}^{i=last\ wet\ gridcel} \tag{2.38}$$

in which:

H_{rms}	local root mean square wave height	[m]
h	local water depth	[m]

It is stressed that the swash factor is applied over the entire wet profile and not only in the swash zone.

2.6 Extrapolation of transport over dry profile

The physical processes taking place near the waterline are not understood well yet and the standard computed transport rates are not valid in the rather shallow swash zone. Therefore the sediment transport in the dry area is determined in a different way by extrapolation of sediment transport over the dry beach until the top of dune.

To be able to execute this extrapolation, a transition point is chosen first. Seaward from this point the initial sediment transport calculation is assumed to be reliable. Landward from this point, an adjusted sediment transport is computed. The computed transport at the transition point is used as a reference transport. The transport landward from the point is expressed as a fraction of this reference transport, depending on the relative bed level and relative wave run-up. In this way the transport depends on the local bed level and thus differs over the entire beach-dune area.

2.6.1 Location transition point

Steetzel (1993) states that the location of the transition point is always located at exactly a quarter of the local wavelength from the waterline. It was chosen to locate the transition point at some distance of the waterline, since flow velocities, sediment concentrations and therefore also sediment transports are difficult to model in very shallow water. A closer look at the model code reveals however that the transition point is located at the last computing point seaward from the waterline. It should be noted that the calculation of the reduction factor does start at ¼ wavelength but the actual extrapolation of transport starts at the last wet gridcel. A quarter of the local wavelength is further only used in determining the relative wave run-up; see Equation (2.40).

2.6.2 Extrapolation method

The transport landward from the transition point is described by the transport S^* in that point times a reduction factor. The basic idea of the reduction factor is to relate the relative transport at a certain level to the relative amount of water which exceeds this level due to wave run up. The extrapolated transport is defined as follows:

$$S\left(x\right)=S^*\left[\exp\left(-2R_z^2\right)-\sqrt{2\pi}R_z\left(1-\frac{2}{\pi}\int_0^{\sqrt{2}R_z}\exp\left(-x^2\right)dx\right)\right] \tag{2.39}$$

in which:

S^*	time-averaged, depth-integrated sediment transport per unit width in last wet computing point	[m^3/m^1/s]
R_z	relative run-up	[-]

$$R_z=\frac{z(x)-z_{sw}}{z_s-z_{sw}} \tag{2.40}$$

z_{sw}	bed level at 1/4 of the local wavelength	[m]
z_s	significant wave run-up above the mean water level	[m]

$$z_s=0.5T_p\sqrt{gH_s}\tan\beta \tag{2.41}$$

in which:

$H_{s,0}$	significant wave at seaward boundary	[m]

$$H_{s,0}=\sqrt{2}H_{rms,0} \tag{2.42}$$

$tan(\beta)$	mean slope of the dune face (between transition point and run-up level)	[m]

The parameters used in the extrapolation method and especially in Equation (2.40) are shown in Figure 2.4.

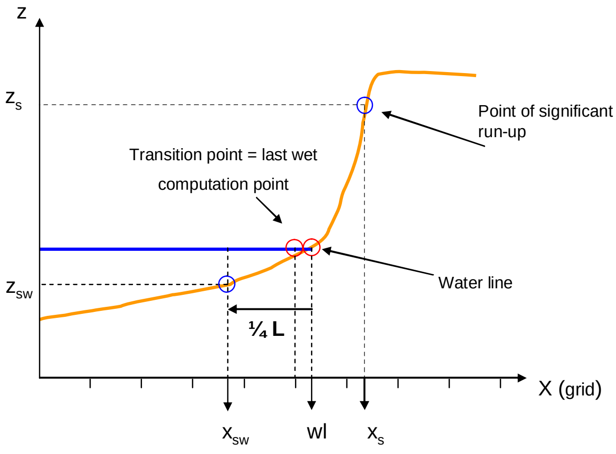


Figure 2.4 Parameters used in extrapolation of transport over dry profile

2.7 Bed level change model

Bottom changes are computed using the conservation equation of sediment mass, according to:

$$\frac{dz_b(x)}{dt} = \frac{-1}{(1-p)}\left(\frac{dS_x(x)}{dx}\right) \tag{2.43}$$

in which:

z_b	vertical coordinate of bed profile with respect to reference level	[m]
p	porosity	[-]
S_x	sediment transport per unit width in cross-shore direction (S/ρ_s)	[m^3/s/m]
S	(time averaged) depth-integrated sediment transport per unit width	[kg/s/m]

The final new bottom profile is computed using a modified numerical LAX-scheme according to:

$$\begin{aligned} z_b(x,t+\Delta t) = z_b(x,t) - \frac{\Delta t}{2(1-p)\Delta x}\left[S_x(x+\Delta x,t) - S_x(x-\Delta x,t)\right] \\ + \frac{1}{2}\gamma\left[z_b(x+\Delta x,t) - 2z_b(x,t) + z_b(x-\Delta x,t)\right] \end{aligned} \tag{2.44}$$

in which:

γ	numerical smoothing factor	[-]

The last term in this equation is the numerical smoothing term. In the calculation of the new bottom profile numerical smoothing is applied to flatten sharp transitions in the bed profile.

3 Analysis of physical model tests

The physical model data used in this research is obtained from the large scale physical model tests that were carried out in the Delta flume of WL | Delft Hydraulics from November 2005 to February 2006. The objective of these tests was to properly simulate dune erosion under severe storm surge for typical Dutch conditions and to get a better insight in the effect of the wave period on dune erosion. This chapter gives a short description of the experimental set-up of these tests. In the second part an extensive data analysis is presented of the, for this research, relevant results. For a more detailed description of the experimental set-up and results of the physical model tests see WL | Delft Hydraulics (2006).

3.1 Experimental set-up

3.1.1 Delta flume

The physical model tests were carried out in the Delta flume of WL | Delft Hydraulics. The flume has an effective length of 225 m, a width of 5.0 m and a height of 7.0 m. The wave generator is equipped with Active Reflection Compensation and 2nd order wave steering. Depending on the water depth and wave period irregular waves with a height up to 1.90 m can be generated.

3.1.2 Model schematisation and scale relations

In the flume a coastal profile was constructed which was based on a reference profile that is considered to be characteristic for the Dutch coast. This schematised reference profile consists of one dune with its top located at NAP+15 m. The slope of the dune face is 1:3. From NAP+3 m to NAP the slope is 1:20 and from thereon the slope is 1:70 to a level of NAP-3m. From this point seaward the slope is finally 1:180. During a characteristic storm the maximum water level reaches the level of NAP +5 m.

During the experiments a depth scale factor of $n_d = 6$ and a profile steepness factor of $S_0 = 2$ were applied. In order to maintain an equal model distortion and steepness factor compared to previous experiments (WL | Delft Hydraulics, 1984), a sediment diameter of D_{50} = 210 μm was desired. Measurements during the different tests showed a mean grain size of D_{50} = 200 μm. This value will be used in this research. In addition to sediment diameter measurements fall velocities were measured during the different tests. This resulted in fall velocities of w_s = 0.023 m/s for tests T01 and T02 and w_s = 0.022 m/s for the other tests.

The actual coastal profile as used in most of the Delta flume tests is shown in Figure 3.1. All tests were carried out with a water level of 4.50 m above the flume bottom. The figure also shows the location of nine pressure sensors along the flume wall. These pressure sensors will be discussed in Paragraph 3.1.4.

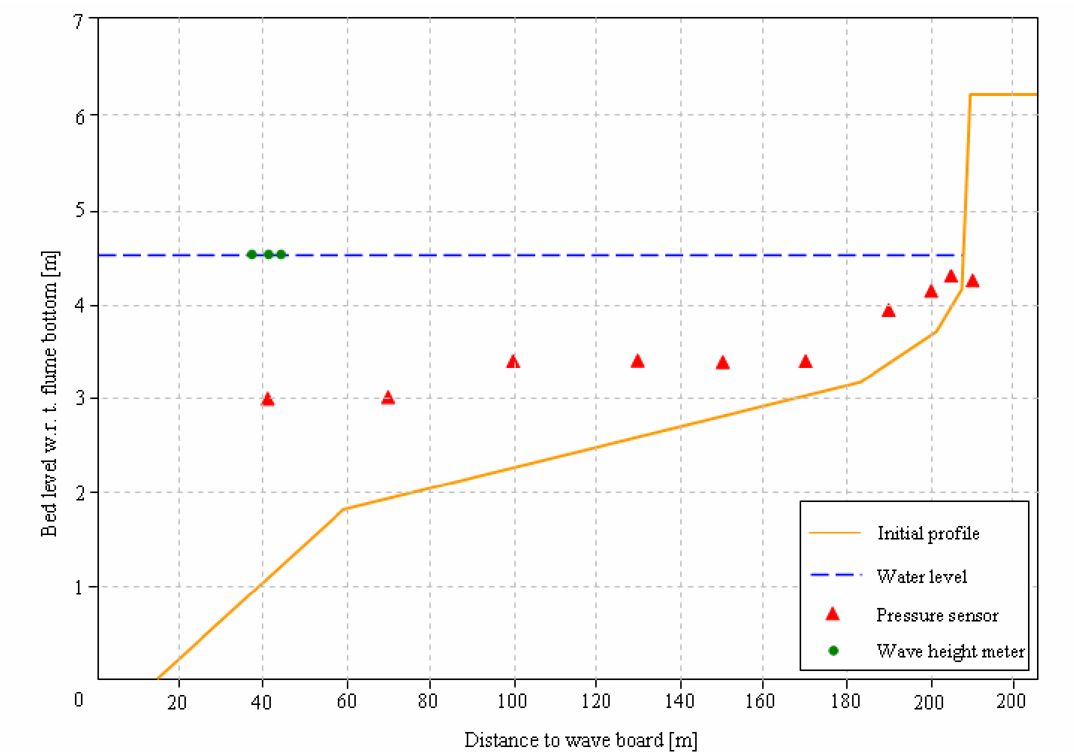


Figure 3.1 Initial profile Delta flume tests

3.1.3 Test programme

An overview of the test programme with the applied hydraulic conditions (near the wave board) is shown in Table 3.1.

Table 3.1 Test programme

Test	Subtest	Start (h)	End (h)	H_{m0} (m)	T_p (s)	$T_{m-1,0}$ (s)	s_p (-)	$s_{m-1,0}$ (-)
T01	A-E	0.0	6.0	1.5	4.9	4.45	0.040	0.049
T02	A-E	0.0	6.0	1.5	6.12	5.56	0.026	0.031
T03	A-E	0.0	6.0	1.5	7.35	6.68	0.018	0.022
T05	A-E	0.0	6.0	1.5	7.35	6.68	0.018	0.022
	F	6.0	7.0	0.8	7.35	6.68	0.018	0.022
T06	A-E	0.0	6.0	1.5	4.9	4.45	0.040	0.049
	F	6.0	6.5	1.5	4.9	4.45	0.040	0.049
	G	6.5	8.5	1.5	7.35	6.68	0.018	0.022
	H	8.5	9.5	0.5	7.35	6.68	0.006	0.007
	I	9.5	11.7	1.4	5.00	4.45	0.036	0.044
T08	A-E	0.0	6.0	1.5	7.35	6.68	0.018	0.022
DP01	A-E	0.0	6.0	1.5	6.12	3.91	0.026	0.063
	F	6.0	7.0	0.50	7.35	6.68	0.006	0.007
DP02	C-E	0.0	6.0	1.5	7.35	5.61	0.018	0.031

During the first six hours of tests T01 till T06, the wave period was the only variable parameter. In test T08 the initial profile was different from the earlier described reference profile to be able to examine the influence of the initial profile. Like in preceding experiments a single peaked Piersson-Moskovitz spectrum was applied. Only in tests DP01 and DP02 a double-peaked spectrum was used.

In this research the influence of the wave period on the amount of dune erosion is an important aspect. In this respect only the results of first 6 hours of each test are relevant. During this period constant hydraulic conditions are applied making it possible to compare the tests and analyse the impact of the increasing wave period. Tests were temporary interrupted at fixed time intervals within the first six hours to perform profile measurements:
Subtest A: 0.00-0.10 hour
Subtest B: 0.10-0.30 hour
Subtest C: 0.30-1.00 hour
Subtest D: 1.00-2.04 hour
Subtest E: 2.04-6.00 hour

An interruption of the tests at 2.04 hours is applied because this moment agrees with a storm duration of 5 hours in prototype. Storms with this duration are used in the safety assessment of the dunes.

3.1.4 Measurements

After each subtest (A-E) the entire profile was measured in three cross-sections. Averaging the results of these three parallel measurements gives the average profile measurement which is used in this research.

Except for the profile measurements also other measurements were performed. The purpose of these measurements was to gain a better insight in the physical processes that are important in case of dune erosion under a storm surge. The measurements were obtained with the following four different clusters of instruments:

- Instruments on the flume wall. The purpose of these instruments was mainly to obtain information on wave transformation over the entire profile.
- Instruments on a shallow water frame. This shallow water frame was used to obtain data on the vertical structure of the flow field, sediment concentrations and sediment transports in the near-shore area. In each subtest the frame was placed at several cross-shore locations.
- Instruments on a deep water frame. The deep water frame was used to obtain more knowledge of sediment transports under sheet flow conditions.
- Stereo video technique was applied to measure the near shore bathymetry and water surface elevation.

In this study only the measurements of the first two clusters of instruments are used. The instruments from these two clusters will be used in this research and are briefly described below.

The instruments on the flume wall were especially applied to obtain more information about the wave transformation over the entire flume, see also Figure 3.1. The incident wave conditions were measured with three wave height meters at short distances of the wave board. The surface elevation over the entire profile was measured continuously with 10 pressure sensors that were located at several locations along the flume. The last pressure sensor (PS10), located in the dune at the start of the tests, is not used in this research because of unreliable measurements. From the measured surface elevations the characteristic wave conditions can be calculated for different time intervals.

On the shallow water frame different kinds of instruments were fixed which were synchronized with the instruments on the flume wall. Eight current velocity meters and ten suction tubes were applied in the vertical to obtain data of the vertical structure of respectively the flow velocities and the sediment concentrations. In addition to the pressure sensors along the flume, another pressure sensor was deployed on the shallow water frame to measure the surface elevation. An overview of the vertical position of the velocity meters and suction tubes deployed on the shallow water frame is given in respectively Table 3.2 and Table 3.3.

Table 3.2 Vertical position of velocity meters on shallow water frame relative to local bed level

Velocity meter	Distance to bed level in tests T01, T03 and DP02 [m]	Distance to bed level in tests T05 and T06 [m]	Distance to bed level in tests T08 [m]
EMS04	0.06	0.44	0.44
EMS05	0.11	0.19	0.06
EMS06	-	0.11	0.11
EMS07	-	0.06	0.08
EMS08	0.32	1.07	1.07
EMS09	0.44	0.94	0.94
EMS10	0.64	0.64	0.64
EMS11	0.95	0.74	0.74

Table 3.3 Vertical position of suction tubes on shallow water frame relative to local bed level

Suction tube	Distance to bed level [m]
ST01	0.04
ST02	0.06
ST03	0.08
ST04	0.11
ST05	0.14
ST06	0.19
ST07	0.29
ST08	0.44
ST09	0.64
ST10	0.94

During each subtest the frame was placed at several cross-shore locations. Most of these measurement intervals have a typical duration of ten to twenty minutes. An overview of the measurement programme of the shallow water frame is given in Appendix A.

The measurements from the shallow water frame form a unique dataset. In previous experiments no such extensive measurements were executed this close to the dune. Most important processes during dune erosion take place in this near-dune area and to obtain a reliable safety assessment method it is important that a dune erosion model is able to represent these processes well. This makes the results of the shallow water frame very valuable for this research.

3.2 Data analysis

As a first step in the data analysis it is necessary to make a selection of the data that are considered useful for this study. To study the performance of DUROSTA regarding the influence of the wave period, two aspects are important. At first the assessment of the wave period dependency requires enough data from tests with different wave periods. It would be best to use data of all three applied wave periods i.e. T_p=12s, T_p=15s and T_p=18s (prototype scale). From this point of view basically the measurements of the first six hours of all tests T01 (T_p=12s), T02 (T_p=15s), T03 (T_p=18s), T05 (T_p=18s) and T06 (T_p=12s) are useful.

An important part of this study is the examination of the individual performance of DUROSTA sub models. The sediment transport in DUROSTA is computed from the time averaged flow velocities and time averaged sediment concentrations. In this respect it is useful to compare the computed velocity and concentration verticals with measured verticals close to the dune. For this extensive analysis accurate data of measured flow velocities and concentrations is required. As described in the previous paragraph the shallow water frame has been used during the tests to measure flow velocity and sediment concentration distributions over the vertical. At first sight however, only measurements from the frame during tests T05 and T06 provide enough data to perform an extensive analysis of the sub models. During tests T01, T02 and T03, data collected with the shallow water frame was limited and was obtained at a relatively large distance from the dune. As a result the data analysis focuses especially on the measurements of the first 6 hours of tests T05 and T06, see Table 3.4.

Table 3.4 Overview of hydraulics conditions for tests T06 and T05

Test	$T_{prototype}$ (s)	H_{m0} (m)	T_p (s)	$T_{m-1,0}$ (s)	s_p (-)	$s_{m-1,0}$ (-)
T05	18	1.5	7.35	6.68	0.018	0.022
T06	12	1.5	4.90	4.45	0.040	0.049

Although a period of 15 seconds is not present in the dataset now, mutual comparison of these two tests can still give insight in wave period dependency.

In the next paragraphs a detailed data analysis is described of the following measurements:

- Erosion profiles and volumes
- Wave height and water level
- Flow velocities
- Sediment concentrations
- Sediment transport

3.2.1 Erosion profiles and volumes

During the experiments the cross-shore profiles were measured after each subtest. The results of these measurements for test T05 and T06 are shown in the left plots in Figure 3.2. Erosion volumes are calculated from the difference between the initial profile and the measured profile after each subtest. The right plots show the development of the erosion volumes and deposition volumes in time for both tests. The erosion volume is defined here as the full amount of eroded material above and below the mean water level.

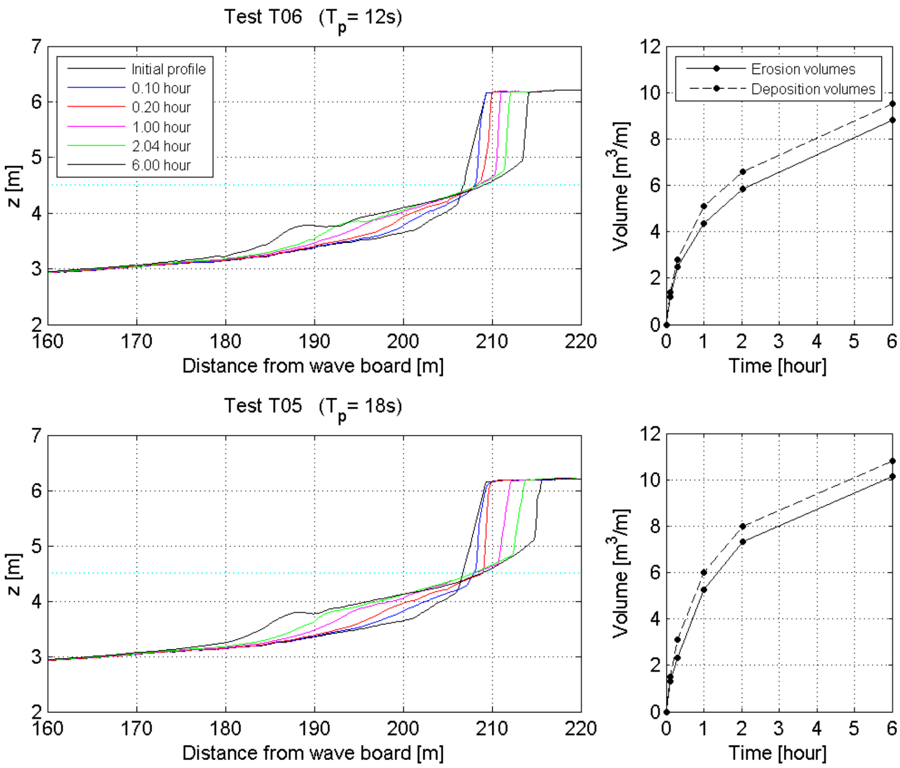


Figure 3.2 Development of erosion profiles and erosion volumes during test T06 (T_p=12s) and test T05 (T_p=18s)

From the figures can be concluded that the dune erosion starts at the toe of the dune for both tests. The slope of the dune face gets steeper until it is nearly vertical. From this point the dune face retreats in time with a decreasing height. During the remaining part of the experiments the dune face retreats and the height of the dune face decreases. The retreat of the dune face is clearly non linear in time. This is also observed in the development of the erosion volume in time, the right plots in Figure 3.2.

After six hours the height of the dune face is comparable for both tests. However the dune face has retreated approximately 1.5 m further for test T05, which indicates more erosion in the case of a larger wave period. Also the measured erosion volumes show more erosion for test T05. In the case of the larger wave period approximately 15 percent more erosion occurs after six hours. After 2.04 hours, which agrees with a storm duration of 5 hours in prototype, the amount of erosion is even 25 percent larger. The relative period effect gets thus smaller in time.

The deposition volumes are approximately 7 percent larger than the erosion volumes. Differences in erosion and deposition volumes are a known phenomenon. Steetzel (1994)

attributes it to differences in porosity of material from the dune and the deposited sand in front of the dune. However, in the model tests that were used in that research, the deposition volumes were lower than the erosion volumes. It was therefore concluded that because of the low density of the sand on the dune and the highly packed deposited material, lower deposition volumes occurred. In this case the conclusions would thus be the opposite. This aspect is further elaborated in Paragraph 4.2.5 in the analysis of the sediment transports.
The deposition area lays only slightly further seaward for test T05. At the end of the deposition area a small bar can be distinguished for both tests.

Comparison of the measured profiles of these tests with the measured profiles during test T01 and test T03 (same hydraulic conditions as are applied for test T06 and test T05), showed that the experiments can be reproduced well (WL | Delft Hydraulics, 2006).

3.2.2 Wave height and water level

As described in Paragraph 3.1.4 the water level variation over the flume was measured continuously at several fixed cross-shore locations. From these measurements wave characteristics can be derived for all subtests. The upper left plots in Figure 3.3 and Figure 3.4 show the wave height decay over the coastal profile for tests T06 and T05 for the first time interval (related to the measurement intervals of the shallow water frame) of each subtest. In the three plots for each test a distinction is made between respectively the root-mean-square wave height for combined low and high frequency waves (upper plot) and the root-mean-square wave height of solely high (middle plot) and solely low (lower plot) frequency waves. Low frequency waves (in wave spectrum) are defined in this study by a wave period larger than two times the peak period imposed at the wave board. This distinction is made considering the detailed investigation of the wave model in DUROSTA later, which is only able to simulate short waves. The root mean square wave height is here defined as $2\sqrt{2m_0}$. The upper plots also show mean water level variations for the same time intervals.

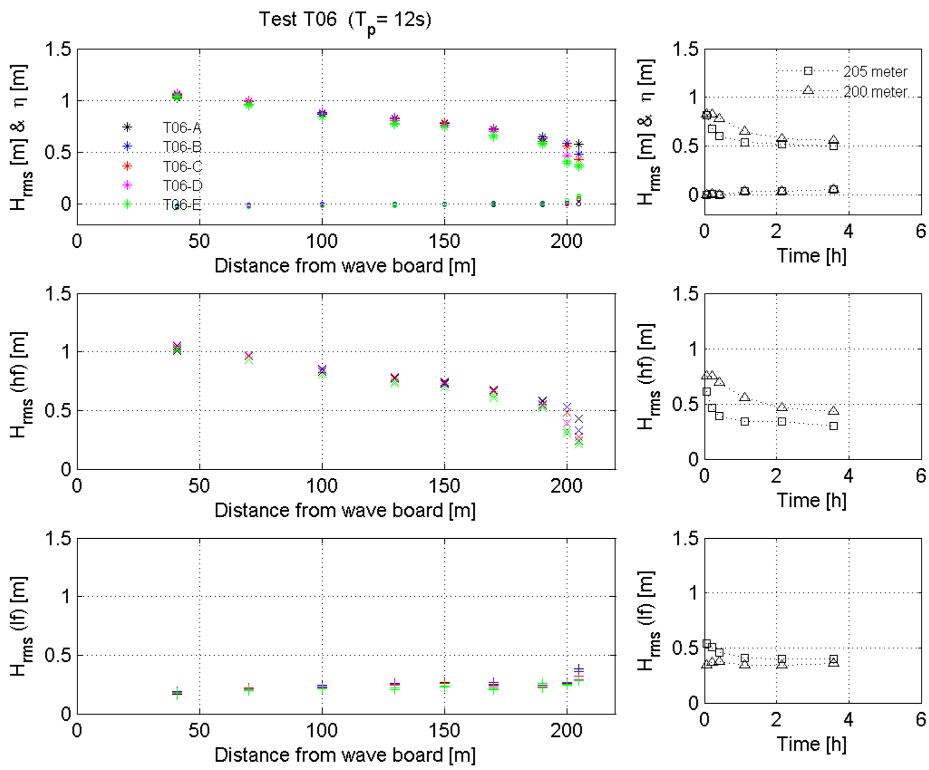


Figure 3.3 Wave height decay over flume for combined high and low frequency waves (upper plot), solely high frequency waves (middle plot) and solely low frequency waves (lower plot), test T06 (T_p=12s). The upper plot also shows mean water level variations.

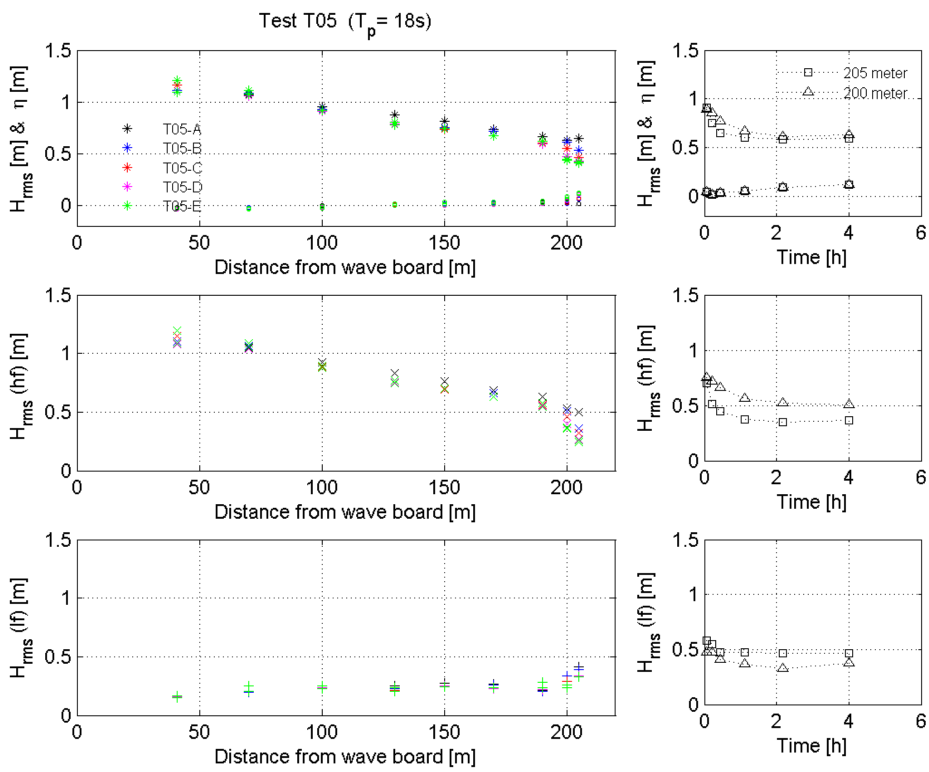


Figure 3.4 Wave height decay over flume for combined high and low frequency waves (upper plot), solely high frequency waves (middle plot) and solely low frequency waves (lower plot), test T05 (T_p=18s). The upper plot also shows mean water level variations.

In the upper plots the wave height decay over the flume, as a result of energy dissipation due to bottom friction and breaking of waves, can be clearly observed. Closer to the dune, in very shallow water, the decrease in wave height is largest.

The measurements also show variations in time which become larger in the vicinity of the dune. Near the dune a strongly decreasing wave height is visible as a result of bed level changes in time. The right plots show that the wave height decreases in time more clearly at 205 m and 200 m from the wave board. Especially in the beginning of the test the wave height decreases quickly at these locations. During test T05 the pressure sensor at 41 m from the wave board shows also a relatively large wave height variation in time. However no real trend is visible and the origin of this variation is not clear. The wave height at this location is slightly larger than the wave height generated at the wave board.

It is observed that, depending on the cross-shore position, the wave height is in general slightly larger throughout test T05. Close to the dune face, at 205 m, 10-15 percent more wave energy reaches the dune face throughout the test.

Landward from 150 m from the wave board there is an increasing water level set-up for both tests. The set-up reaches values between 0.1 m and 0.2 m at 205 m. The setup is slightly larger for test T05 which can be explained by the in general also larger wave height during test T05. Because of continuity of water mass in the flume there is small set-down of mean water level seaward from 150 m from the wave board.

In the lower two plots of each figure a distinction is made between wave height of respectively high frequency and low frequency waves. From these graphs can be concluded that low frequency waves become more important near the dune. This can be explained by the fact that the shorter waves are breaking in the surf zone, whereas the low frequency waves lose much less energy.

3.2.3 Flow velocities

During the experiments undertow flow velocities were measured at different cross-shore locations with the shallow water frame. Especially at measurement locations near the dune the local water depth is limited. At these locations current velocity meters higher in the vertical will often come partly or completely out of the water and measurements of these velocity meters are therefore not reliable. Hence, all measurements above the local mean wave trough level are discarded in this analysis.

The figures in Appendix B.1 show all the measured velocity verticals at 205, 200, 195, 190, 185 and 180 m from the wave board for tests T05 and T06. In order to measure time averaged flows, flow velocity sensors were calibrated in still water. During test T05 this calibration took place in shallow water, which is not preferable since, due to the proximity of the bottom and water surface, the calibration might cause an artificial offset to the flow devices. It the next part it is found that EMS06 had such an offset. Time-averaged flow velocities from EMS06 during test T05 are therefore not included in the further analysis.

From the verticals it seems that for both tests the velocities slightly increase towards the dune (except for 200 m and 205 m). Remarkable is the consistently relative high value of the second velocity meter from the bottom in test T05 (EMS06). As a result in almost all velocity verticals (except during subinterval D at 195 meter) a spike can be distinguished near the bottom. Especially for the locations 205, 200 and 195 m from the wave board this results in rather questionable verticals. In test T06 a spike is only visible in measurements at 205 m from the wave board, although not as pronounced as in test T05. As showed in Table 3.1 for test T08 the same hydraulic conditions were applied as for test T05. During the first three subtests, no large differences in profile development are observed between those two tests. It is therefore possible to compare measured velocity profiles during those three subtests to get a better insight in the accuracy of the velocity measurements during test T05; this is shown in Appendix B.1.1. From these figures it can indeed be concluded that, especially for the measurements at 205 m, the spike near the bottom is unrealistic. In the remaining part of this research measurements EMS06 are removed from the dataset for test T05. Based on the comparison of the verticals of T05 with the verticals of test T08 and the fact that the measurements do not clearly show large deviations compared to test T06, the velocity measurements of test T05 are still assumed to be useful for this research, in any case for qualitative comparisons.

The shape of the velocity verticals is not as curved as based on the theory might be expected, see also Figure 2.2. For both tests the verticals do not have a curved shape but are more upright (neglecting the measurements of the second velocity meter in T05). Only at 185 m from the wave board a real curved vertical is measured.
To be able to obtain better insight in the behaviour of the flow velocities in time and space, all measured velocity verticals are integrated over depth. The method used for this integration is based on a procedure described by Reniers *et al*. (2004):

$$\int u_m dz = \frac{1}{z_N} \sum_{j=1}^{j=N} \left(u_{m,j} + u_{m,j-1}\right)\left(z_j - z_{j-1}\right)/2 \qquad (3.1)$$

where the subscript m refers to the measured velocities and j corresponds to the individual velocity meters. In this method the velocity verticals are integrated up to the highest reliable velocity meter. Therefore z_N corresponds to the position of the uppermost meter that is still below the mean wave trough level. The velocity at the bed $u_{m,0}$ is assumed to be zero. The integration method is visualised in Figure 3.5, were the triangular points represent the measurements of the velocity meters.

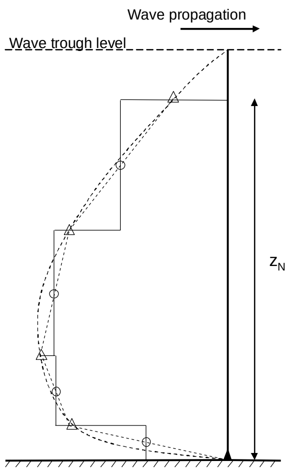


Figure 3.5 Integration method velocity profiles

Figure 3.6 and Figure 3.7 show the depth averaged velocities in time and space for tests T06 and T05.

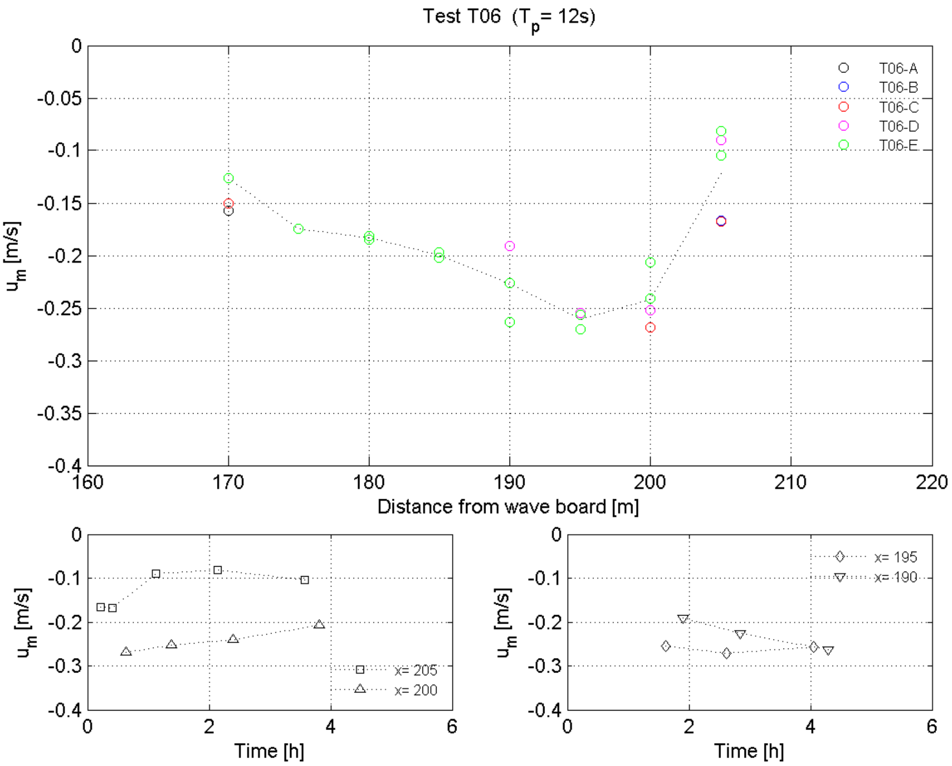


Figure 3.6 Depth averaged velocities test T06 (T_p=12s) in space (upper plot) and time (lower plot)

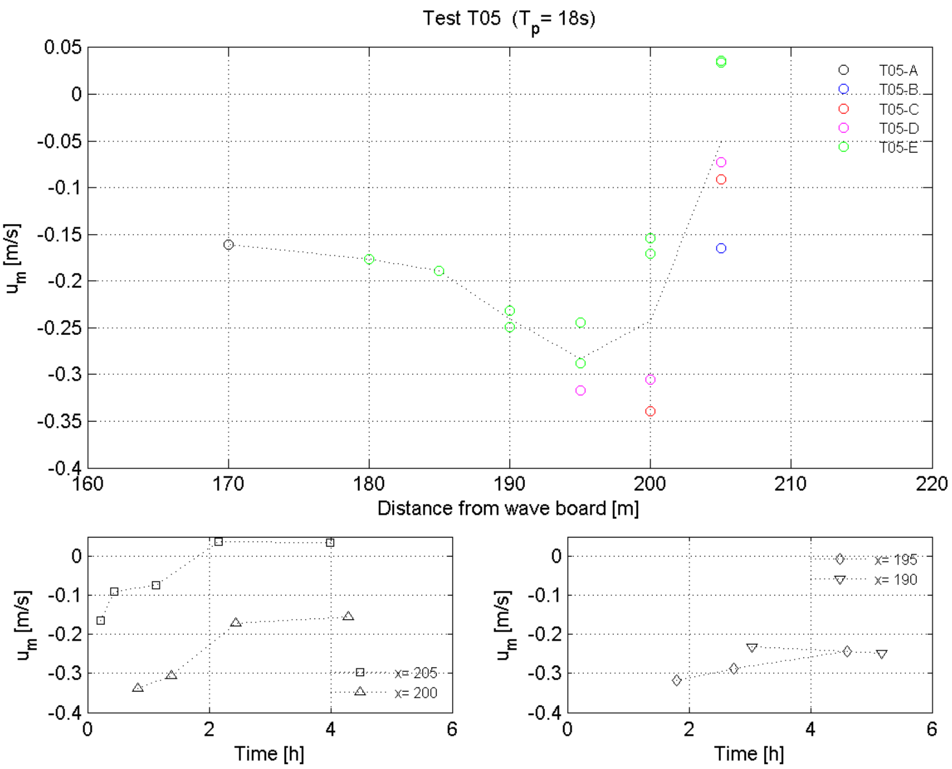


Figure 3.7 Depth averaged velocities test T05 (T_p=18s) in space (upper plot) and time (lower plot)

The depth averaged velocities lay in a range of approximately -0.05 m/s to -0.35 m/s for both tests.
The mean seaward directed velocities are clearly increasing from 170 m to 195 m from the wave board, closer to the dune the velocities decrease again. The positive velocities at 205 m for test T05 are an exception and imply a flow in the onshore direction. It should however be stressed that measurements on 205 m are performed in very shallow water, where we expect strong gradients in velocities over the water depth. It should be questioned whether so few (usually even one) measurements in the vertical are able to give reliable results in this respect.

In general no large differences are distinguished between the two tests. Based on the slightly higher wave height for test T05, also larger undertow velocities are expected. This is however not clearly observed in the velocity measurements.

The lower plots show the development of mean undertow velocities in time for the four measuring locations of the shallow water frame nearest to the dune. From these plots can be concluded that the velocities are decreasing in time at 205 m and 200 m. This is also expected based on the strongly decreasing wave height at these locations. The decreasing wave height results in less mass transport towards the dune and therefore decreasing undertow velocities. Further from the dune no general trend can be distinguished for both tests.

3.2.4 Sediment concentrations

With the suction tubes deployed on the shallow water frame sediment concentrations were measured in the vertical. To select the reliable measurements of the suction tubes another criterion is used than for the flow velocity measurements. In contrast to measurements from the velocity meters, measurements of a suction tube are not expected to become unreliable when the tube comes out the water. Therefore all suction tubes below the local mean wave crest are taken into account in this analysis.

The sediment concentration verticals are shown in the figures in Appendix B.2 for both tests T06 and T05. At first sight these verticals seem reliable for both tests and the large number of measurements in the vertical gives rather smooth profiles. No remarkable irregularities are observed, except for the fact that sometimes the most upper measurement shows a larger concentration than the measurements below. This was observed in other researches, e.g. Van Rijn (1993).

To gain better insight in the behaviour of sediment concentrations in time and space the sediment concentration verticals are integrated over depth. The integration method is the same as used in the integration of the velocity verticals in the previous paragraph. The only difference is that the concentration at the bed is assumed to be equal to the sediment concentration from the lowest suction tube. This may result in an underestimation of the actual mean concentration because of the relative high concentrations gradients near the bed. The sensitivity of the results was studied by integration of a least square fitted exponential function through the data points. Calculation of depth averaged concentrations with this method showed comparable results. Therefore the initial applied method is regarded as a good estimate, and will be applied in this research.

Figure 3.8 and Figure 3.9 show the depth averaged sediment concentrations as a function of the distance to the wave board (upper plot in each figure), as well as the development of concentrations in time at the four measurement locations closest to the dune (lower plot in each figure). Note that the scale of the y-axis is different for both tests. It is remarked that sediment concentrations are integrated to the first suction tube below the mean wave trough level and thus not over the whole water depth. Integration over the whole water depth would result in smaller depth averaged concentrations. The first approach is chosen since DUROSTA also computes the seaward directed sediment transport from depth averaged velocities and concentrations below the mean wave trough level. It makes it possible to directly compare the measurements and DUROSTA computations later on in this research.

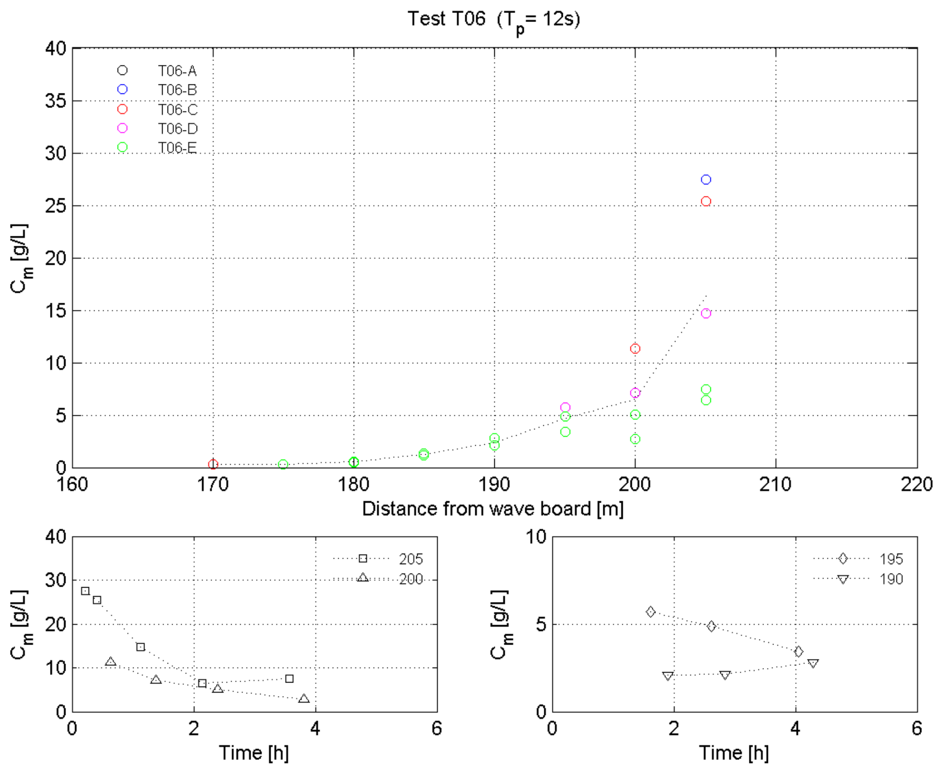


Figure 3.8 Depth averaged sediment concentrations test T06 (T_p=12s) in space (upper plot) and time (lower plot)

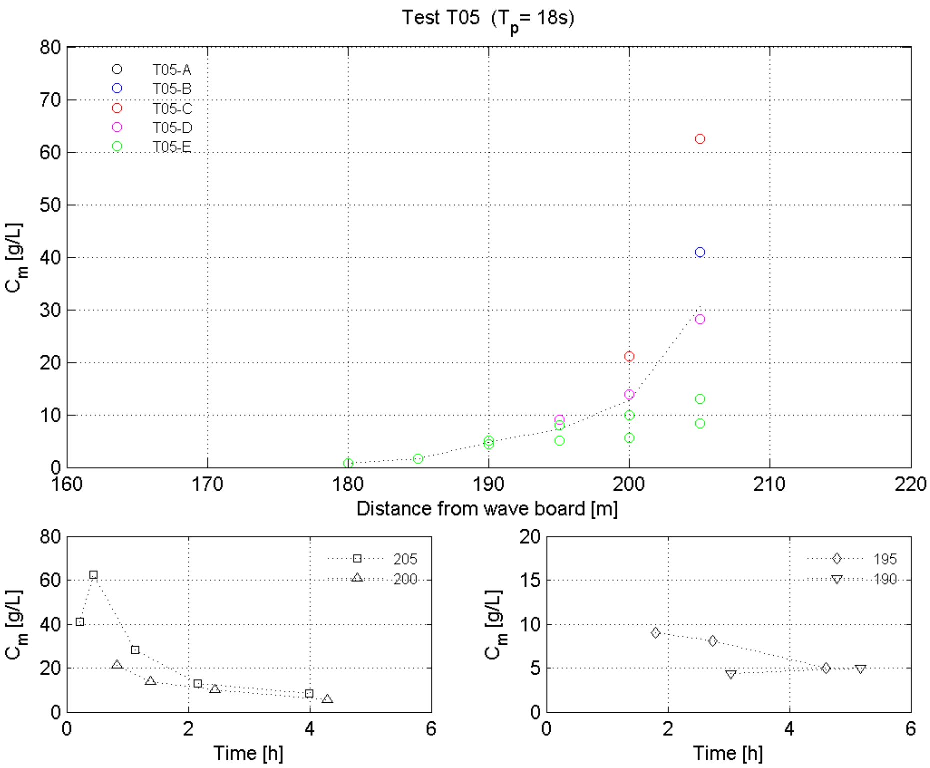


Figure 3.9 Depth averaged sediment concentrations test T05 (T_p=18s) in space (upper plot) and time (lower plot)

It is concluded that average sediment concentrations increase quickly towards the dune for both tests. The high variability of the sediment concentrations in space is rather different from the variations in flow velocities. The variability of the flow velocities lies in a rather small range and reaches maximal differences in the order of factor 3. Variations in concentration are however much larger and can reach values in the order of factor 50.

In the lower plots the development of the mean concentrations in time is presented. It is observed that the concentrations decrease very quickly in time for the near-dune locations (205 m and 200 m from the wave board). Also at 195 m a decreasing trend is observed. Further from the dune, at 190 m from the wave board, the concentrations slightly increase in time.

The measurements of test T05 show consistently higher values than the measurements of test T06. The difference in sediment concentrations between the two tests vary in the order of a factor two. Combined with the comparable velocities this indicates a larger transport capacity in front of the dune in the case of larger wave periods.

3.2.5 Sediment transport

Sediment transports are derived from multiplying measured flow velocity and sediment concentration verticals and from the measured bed level change. Both methods are described in more detail.

Sediment transport derived from verticals

From the measured flow velocities and sediment concentrations transport verticals are derived. This is done by multiplication of measured velocities and concentrations at the same height in the vertical. Since there are more measurements of sediment concentrations in the vertical, some of these measurements are thus not used. The figures in Appendix B.3 show the resulting sediment transport verticals. Remarkable is the almost triangular shape of the verticals with a top close to zero.

From the sediment transport verticals depth averaged values are calculated in the same way as done for the velocities. For the same reason as was mentioned in the previous paragraph the sediment transport is only averaged over the depth under the mean wave trough level. In reality also a shoreward directed sediment transport is present above the wave trough. This shoreward transport is included in DUROSTA and to be able to compare the measurements and calculations as good as possible this transport should also be included in the measurements. This is done in the same way as DUROSTA computes the onshore directed transport. Assuming conservation of mass flux and a constant concentration above the wave trough, the shoreward directed transport above the wave trough is described by the product of the discharge below the wave trough and the concentration of the upper suction tube below the trough:

$$S_u = \left(u_{m,l} h_{tr}\right) * c_{tr} \tag{3.2}$$

where $u_{m,l}$ is the mean velocity below to wave trough as calculated in Paragraph 3.2.3, h_{tr} represents the depth below the wave trough and c_{tr} is the concentration measured by the upper suction tube below the trough.

Sediment transport derived from bed level change

Besides the estimation of the sediment transport from the verticals, a mean sediment transport is also derived from the change in bed level between the different subtests. The mean sediment transport over the entire profile is calculated from the bed level change as follows:

$$S(x) = \int_{x=220}^{x=0} \frac{dz}{dt} dx \left(1 - n_p\right) \tag{3.3}$$

Theoretically this method assumes a zero transport at the beginning of the profile (at the wave board). However the balance does not close and the sediment transport gets larger than zero at this location. The problem of a non closing transport balance was also encountered in other research projects and different explanations are used. Steetzel (1994) relates it to differences in porosity of sand on the dune and the deposited sand in front of the dune. In this case however, sediment transport was negative and it seemed like sediment had

disappeared which is opposite to the conclusions above. Another explanation is errors in the measurements of the profiles. Especially the transport calculations for subtest A (and B in test T05) showed that the transport still increased at large distance from the dune. Since bed level changes are expected to be negligible here, in this case the difference is associated with measurement errors or the method of determination of the mean profile.
As described in Paragraph 3.1.4 a profile is used which is determined from the average of three measured cross-shore transects. However after each test a curvature of the bed was observed in the cross-flume direction. This curvature becomes more pronounced at larger distances from the dune and probably results in an overestimation of the profile when averaging the three transects. When the curvature develops during the first part of the tests it may explain why a positive sediment transport is calculated near the wave board for these subtests. Further study of the development op de cross-flume curvature is required to give a sound explanation for the increasing transports. In this study the problem is solved by cutting of the sediment transport graph at 160 m from the wave board. It is expected that no net sediment transport takes place seaward from this point. The surplus in transport at this location (in the order of $0.3*10^{-3}$ $m^3/m/s$ for subtest A) is distributed equally over the profile between the point of the maximum sediment transport (at the toe of the dune) and 160 m. In this way the balance is artificially closed at 160 m. It can be argued not to distribute the error equally over the profile because the curvature becomes more important closer to the wave board. However the origin of the error is not entirely certain and also porosity differences can still play a role. Therefore it is chosen to distribute the error over the profile between the toe of the dune and 160 m.

In Figure 3.10 and Figure 3.11 the dots represent the results of integration of the sediment transport verticals for both tests. The solid lines in the upper plots gives the mean sediment transports as is derived from the change in bed level in the different subtests. It is remarked that the solid lines represent the mean transports over an entire subtest. The dots represent mean transports only over a certain interval (related to shallow water frame measurements) in a subtest. Close to the dune (at 200m and 205m) most of the measurements were executed at the beginning of a subtest and measurements further away from the dune were performed more to the end of a subtest. This may lead to a small overestimation of the mean values for a subtest at locations close to the dune and a small underestimation further away from the dune.

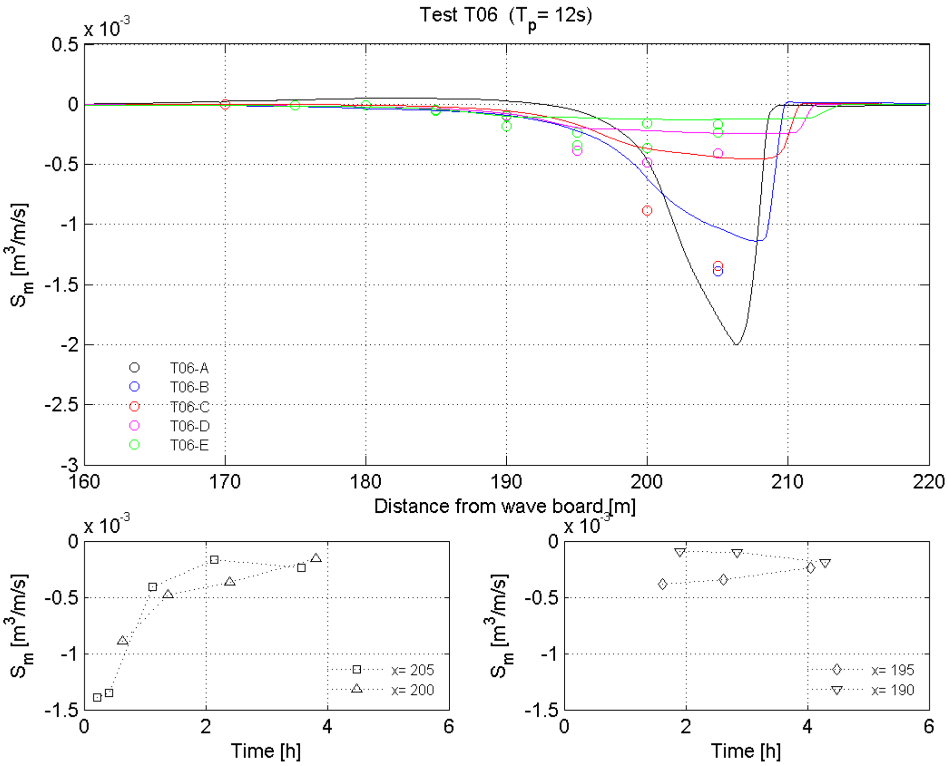


Figure 3.10 Mean sediment transport from verticals (dots) and from bed level change (solid lines), test T06 (T_p=12s)

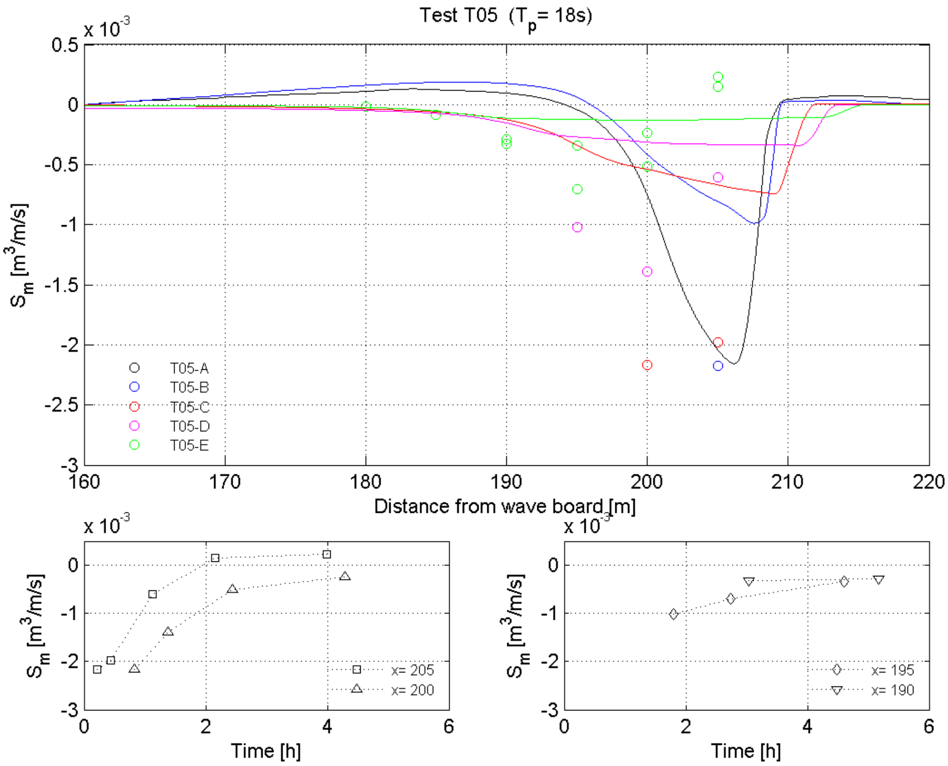


Figure 3.11 Mean sediment transport from verticals (dots) and from bed level change (solid lines), test T05 (T_p=18s)

In the sediment transport graphs is observed that most of the sediment transport takes place between 180 m and 210 m. For the calculated depth averaged transports roughly the same trends are visible as in the analysis of the depth averaged sediment concentrations. This is caused by the relatively large variations in concentrations compared to the relatively constant velocities in space. The (development of) sediment transport is therefore mainly controlled by the amount of suspended sediment rather than by the undertow velocities.

Comparison of the transport determined from the bed level change and the sediment transport verticals shows that trends in time and space are roughly comparable. The agreement is however much better for test T06, especially for subtests D and E. The depth averaged values from the verticals are especially for the first three subtests of test T05 much larger. Characteristic for the solid lines is the slow decreasing transport (seaward direction) in front of the dune during subtest C, D and E. This means that only a small amount of sedimentation occurs in this area. This trend can also be distinguished in the transports derived from verticals for subtest D and E in test T06 and in subtest E of test T05.

The sediment transport is in general larger for test T05 than for test T06, this is also expected based on the almost equal velocities but much larger concentrations. Differences between the two tests are however much smaller, based on transport derived from bed level change compared to the sediment transport derived from verticals.

It is stressed that differences between the two methods are significant. This can be explained by the fact that sediment transport derived from the bed level change includes all the physical processes which play a role during the model tests (e.g. also wave induced transports). Sediment transports derived from the verticals are in this respect limited. The method of integration and the limited amount of measurements in the vertical have their influence as well. The differences should however be kept in mind when the measured verticals are compared with the computed verticals by DUROSTA in the next chapter.

4 Performance of DUROSTA sub models

The DUROSTA model is a process-based dune erosion model. In such a model dune erosion is computed on the basis of physical processes. The general idea is that all physical processes, which are important in modelling dune erosion during a storm surge, are included in the model. In DUROSTA these physical processes are represented by the different sub models described in Chapter 2. When the individual performance of these different sub models is good, it is expected that the dune erosion model is able to give a reliable prediction of dune erosion during a storm surge.

In this chapter the performance of the different sub-models is studied. An important part of this analysis examines the performance of the sub models regarding the influence of the wave period using the data analysis described in the Paragraph 3.2. Simulations with the DUROSTA model are carried out for the same hydraulic conditions as in tests T06 (T_p=12s) and T05 (T_p=18s), see Paragraph 3.1.3. Model results are compared with the measurements of these experiments to obtain insight in the performance of the sub models for default input parameters. Mutual comparison of the results for the different wave periods will give a first indication of the quality of the model concerning the wave period dependency. It is stressed that the simulations are carried out for model-scale, and not for prototype-scale.

In Chapter 5 the performance of the DUROSTA model as a whole is examined. Based on these results the relation between the performance of the DUROSTA sub models and the integral performance of the DUROSTA model is studied.

4.1 Computational set-up

To be able to compare measurements directly with computations of DUROSTA sub-models, only initial computations are carried out for tests T05 and T06. This implies that for each measuring interval of the shallow water frame (Appendix A) a new DUROSTA computation is executed. In every computation the bottom is updated with an (interpolated) bottom profile from the measured profiles at the start and the end of the subtest. In this way the profile in DUROSTA is as close as possible to the actual profile in the flume and the effect of differences due to bathymetry are expected to be negligible.

Measurements of wave height, flow velocities, sediment concentrations and sediment transports, described in the data analysis in Paragraph 3.2 are directly compared with DUROSTA computations. The only difference is that the measurements are averaged over the interval (of approximately 10-20 minutes) and that DUROSTA gives the output at the first time step of an interval, when no profile change has taken place yet. In this way it is implicitly assumed that the bed level is approximately constant for 10-20 minutes during the measurements. The DUROSTA computations are carried out for default input parameters, see Appendix C.1 and a constant grid size of 0.5 m.

It is stressed that the described method can only be applied to gain better insight in the hydrodynamics but not in profile development in time.

4.2 Wave propagation model

In DUROSTA the wave height decay over the dune profile is computed with the ENDEC-model. Calibration of the ENDEC-model was executed by determining a best fit of the root mean square wave height decay along the flume (Steetzel, 1990a). The H_{sig} imposed at the wave board in the experiments is used as a boundary condition for the computations.

The results of wave height computed by DUROSTA compared to the measurements are shown in Figure 4.1 and Figure 4.2 for respectively test T06 and test T05. In these figures solid lines represent the model results and dots the measured values. In each figure also a distinction is made between respectively the root-mean-square wave height for combined low and high frequency waves (upper plot) and the root-mean-square wave height of solely high (lower plot) frequency waves. This division is made considering the fact that ENDEC is not able to make a distinction between long and short waves.

In the upper plots of the figures computed and measured variations in mean water level are shown as well.

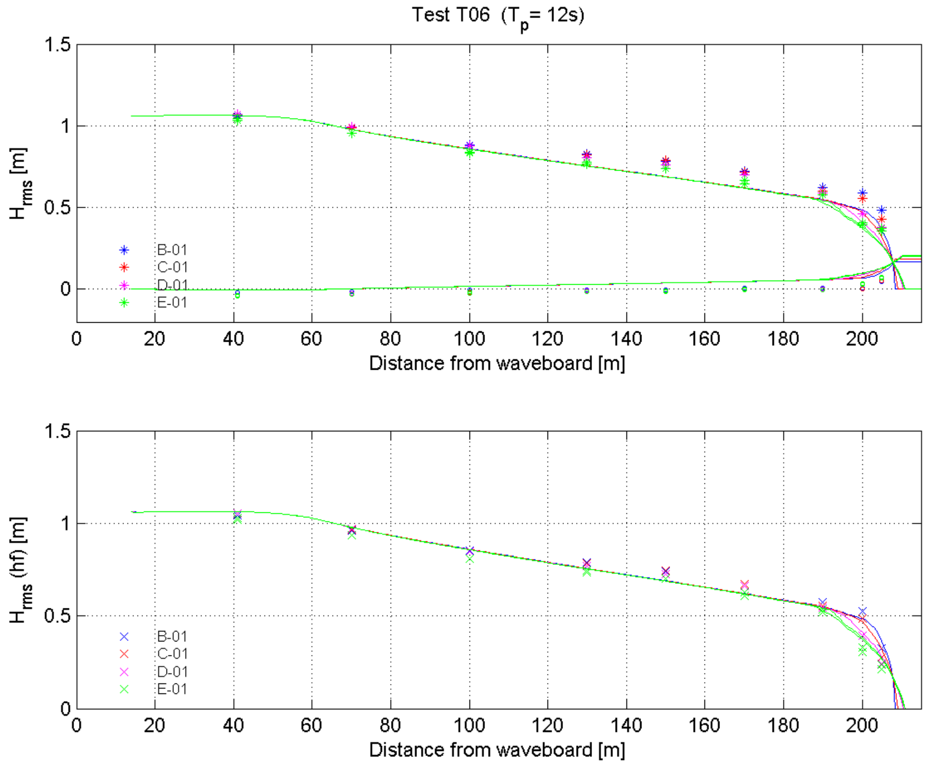


Figure 4.1 Wave height decay from measurements (dots) and DUROSTA (solid line) test T06 (T_p=12s). Upper plot shows root-mean-square wave height for combined low and high frequency waves, lower plot shows root-mean-square wave height of solely high frequency waves

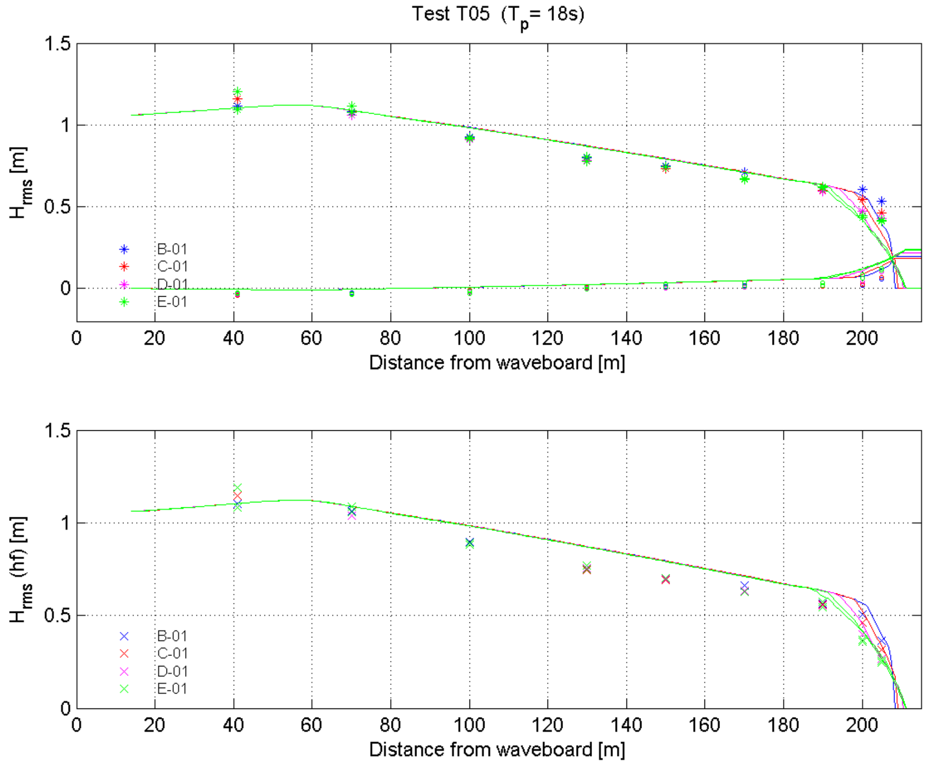


Figure 4.2 Wave height decay from measurements (dots) and DUROSTA (solid line), test T05 (T_p=18s). Upper plot shows root-mean-square wave height for combined low and high frequency waves, lower plot shows root-mean-square wave height of solely high frequency waves

In the computations wave heights are decreasing towards the dune and large variations in time occur close to the dune where energy is dissipated quickly. This tendency is also observed in the measurements.

The measurements of test T05 show a larger wave height at 41 m from the wave board, compared to the wave height generated at the wave board. DUROSTA also computes this increasing wave height at the beginning of the profile. For DUROSTA computations this results in a larger computed wave height over the entire profile for test T05 compared to test T06. The measurements showed a slightly higher wave height for this test as well.

The mean water level computed by DUROSTA overestimates the measurements consistently. Especially close to the dune this overestimation is in the order of 50 percent. This can partly be explained by the fact that DUROSTA does not calculate the decrease in water level as it occurs in the flume. Because of continuity of water mass in the flume, wave set up causes a decrease in water level near the wave board.

The DUROSTA model is not able to make a distinction between long and short waves, the results are therefore compared with measurements of only high frequency waves. This approach can be substantiated by the fact that long waves are mainly reflected and therefore not expected to result in higher undertow velocities. The effect of these long waves should thus (implicitly) be incorporated in the sediment concentration model.
The comparison with only measured high frequency waves indeed shows a better agreement in the case of test T06. In the upper plot DUROSTA underestimates the measurements systematically from 130 m towards the dune. In the lower plot DUROSTA still slightly underestimates the measurements between 130 m and 170 m, but close to the dune the agreement is much better. Later in the experiment even overestimation of the measurements occurs at these locations.
For test T05 the agreement is a less good. When no distinction is made between long and short waves DUROSTA clearly overestimates the wave height between 100 m and 190 m and underestimates at the locations close to the dune. Comparison with only short waves shows that the overestimation is only worse between 100 m and 190 m. Right in front of the dune however, the agreement with the short waves is much better but slightly overestimated.

Earlier studies (Den Heijer, 2005 and Steetzel, 1993) stated that DUROSTA overestimates the wave height near the dune only for large wave periods and would therefore indeed give a higher sediment transport for larger wave periods. However in those studies, no measurements were available at the last three locations in front of the dune. Based on only that information it can indeed be concluded that DUROSTA overestimates the measurements only for test T05. However, the current computations (including the locations close to the dune) show for both tests a slight overestimation of the measurements near the dune (only short waves). It is therefore not expected that a wave period effect is mainly caused by a larger computed wave height (w.r.t. measurements) for test T05.

From these results it can be concluded that the ENDEC-model in DUROSTA performs quite well for default settings (i.e. γ=0.85) in the near dune area. This is quite remarkable since the model was calibrated only with measurements further from the dune and only for wave period lower than or equal to 12 seconds (prototype). In the middle of the profile the agreement is less good. Because the amount of dune erosion is mainly determined by breaking of waves very close to the dune, it is especially important that DUROSTA computes the wave conditions well close to the dune front.

4.3 Cross-shore flow model

As described in Paragraph 2.3 the cross-shore flow model in DUROSTA is based on the time-averaged velocity profile below the mean wave trough level. This time averaged velocity profile consists of three contributions; a uniform, a linear and a logarithmical part. The uniform part or bottom velocity actually determines largely the overall magnitude of the velocity vertical. The logarithmical part, depending on the vertical mixing gradient and fall velocity of the sediment, determines the curvedness of the vertical. In the analysis of the cross-shore flow model several methods are used to determine the performance, i.e. measured velocity verticals, reference velocities and depth averaged velocities. The results are described in the following sections.

Performance based on measured verticals

The figures in Appendix C.2 and C.3 show the measured velocity verticals and the velocity verticals computed by DUROSTA for respectively tests T06 and T05.

For test T06 it is observed that computed velocities increase slightly towards the dune. Also in the measurements this trend can be distinguished except at 205 meter from the wave board, here the velocities are smaller again. For test T06 DUROSTA overestimates especially the lowest velocity meter at 205 m and 200 m from the wave board but agrees quite well with the other meters at these locations. For all other locations in test T06 DUROSTA underestimates the velocities, especially close to the bed. This underestimation becomes larger further away from the dune.
Another remarkable difference between computed and measured verticals is the fact that computed verticals reach much higher and also have a more curved shape. This is caused by the fact that just a few measuring points are available higher in the vertical. Also only measurements from velocity meters below the mean wave trough are taken into account, whereas computed verticals by DUROSTA reach up to the average water depth. Close to the dune, in very shallow water, this results in quite different verticals. Further away from the dune, the computed verticals are getting a more straight shape. This trend is also visible in the measurements, although less clear. In this respect the rather curved measured velocity vertical at 185 m agrees not well with the computed one. The trends in time agree in general quite well for test T06.

For test T05 the tendency of increasing computed velocities towards the dune is also distinguished, except very close to the dune, at 205 m and 200 m from the wave board. The computed velocities at these locations are again a little smaller. Because of the unreliability of the measurements of the second velocity meter above the bed, these measurements are still ignored in the comparison of this test. In general DUROSTA computations overestimate the lowest meter at 205, 200 and 190 m. Like in test T06 computed verticals reach much higher than measured verticals. The results for 190, 185 and 180 m are quite good; however DUROSTA slightly underestimates the measurements for the latter two. Also the shape of the profiles agrees quite well with the measurements at these locations.

Performance based on reference velocity

Since the bottom velocity largely determines the overall magnitude of the velocities computed by DUROSTA, it is interesting to further study the bottom velocity. Obviously bottom velocities were not measured during the experiments and therefore the measurements of the lowest velocity meter are compared to DUROSTA results at the same height. It is stressed that this does not concern the flow velocity at the bed u_0 as is defined in DUROSTA (see Equation (2.13)) but a near bed velocity, u_{ref}.

Figure 4.3 shows the results for both tests. The DUROSTA computations are represented by squares and the measurements by dots. The right plots also show the correlation between computed and measured u_{ref}. By averaging all measurements at a certain location a general trend in space is derived, this is represented by the dotted line for the measurements and the solid line for the computations.

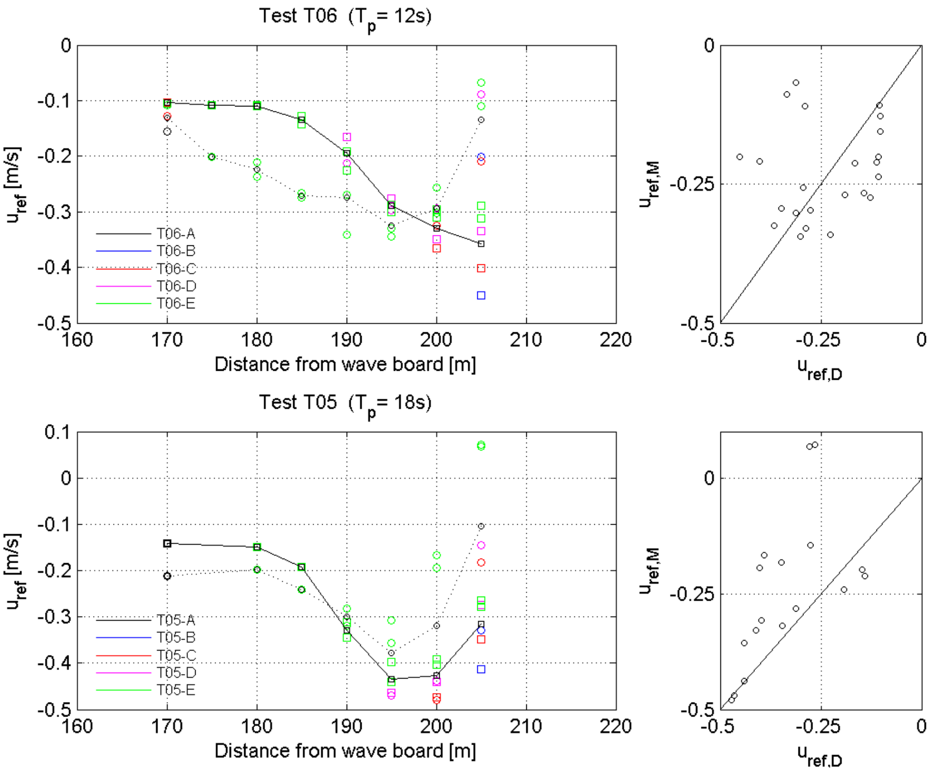


Figure 4.3 Near-bed velocity from measurements (dots and dotted line) and DUROSTA (squares and solid line), test T06 (upper plots) and T05 (lower plots)

For test T06 the computed u_{ref} increases towards the dune as also was observed in the analysis of the velocity verticals. In the measurements u_{ref} increases towards the dune as well, except for 205 m and 200 m. This tendency was also observed in the verticals.

Comparison of the measurements and computations for test T06 shows that DUROSTA underestimates the measured values between 175 m and 195 m from the wave board with, at some locations, even a factor two. DUROSTA overestimates the measurements especially at 205 m, which was also observed before. At this location there is also significant spreading in the results. It is however stressed that measurements at this location are performed in very shallow water and the reliability of these measurements is therefore questionable. This aspect was already described more extensive in Paragraph 3.2.3.

For test T05 the general spatial trend is comparable for measurements and computations and especially further from the dune differences are much less compared to test T06. Between 195 m and 205 m significant spreading is observed again, especially for subtest E. Also from the correlation graphs it can be concluded that the results are relatively well if the velocity measurements at 205 m are not taken into account.

Performance based on depth averaged velocity

As described in Paragraph 2.5 DUROSTA calculates the depth averaged, seaward directed sediment transport from multiplication of the velocity and concentration verticals. In this respect it is also interesting to compare the depth averaged values of the measured and computed velocities. Measured depth averaged velocities are calculated in the same way as in Paragraph 3.2.3. In DUROSTA depth averaged velocities are derived from the conservation of mass flux (see also Paragraph 2.3) and are described by:

$$u_m = \frac{m}{\rho h_{tr}} \tag{4.1}$$

where m is the mass flux computed by DUROSTA as in Equation (2.18), h_{tr} is the local water depth under the wave trough. It should be noted that the roller part is not included in Equation (4.1). In Figure 4.4 measured depth averaged velocities and depth averaged velocities computed by DUROSTA are represented by respectively dots and solid lines.

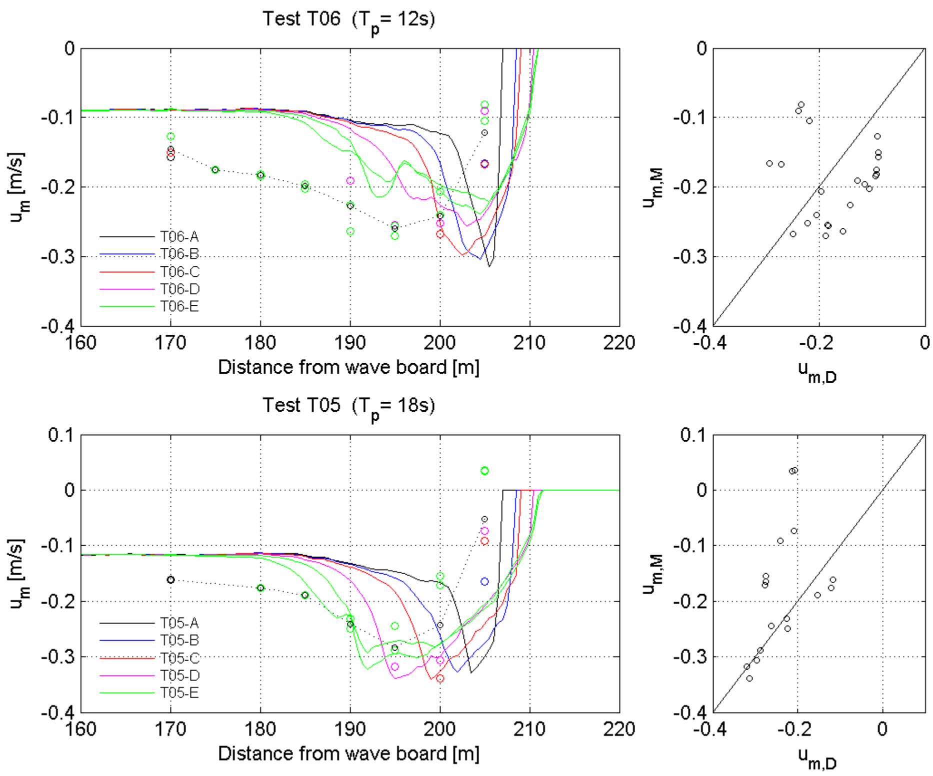


Figure 4.4 Depth averaged velocities derived from measured velocity verticals (dots) and DUROSTA (solid lines), test T06 (upper plots) and T05 (lower plots)

General trends in measurements and computations are comparable; the only difference is the location of the maximum velocities for test T06. For the measurements this peak is located in a more seaward position.

For test T06 DUROSTA underestimates the measurements significantly between 170 m and 195 m and overestimates closer to the dune, just as was seen with the u_{ref}. Again it is stressed that the measurements at 205 m should be used carefully. Also in the case of test T05 approximately the same trends can be observed for u_m as for u_{ref}; slightly underestimating between 170 m and 180 m and overestimating between 195 m and 205 m. When measurements at 205 m are discarded, the correlation diagrams of u_m seem slightly better compared to the diagrams of u_{ref}. Results for test T05 show in general a better agreement between the measurements and DUROSTA computations compared to test T06.

It is remarkable that DUROSTA underestimates the velocities especially further from the dune in test T06. An underestimation up to a factor two occurs, just as was seen with u_{ref}. The underestimation can at first sight not only be explained by differences in wave height, since the wave propagation model performed well in this area. Also the integration method is not assumed to be the origin of this difference because the same differences are also observed in the verticals (Appendix C.2) and analysis of u_{ref}. In Appendix C.4 a more extensive analysis is performed to be able to explain the underestimation of the velocities further from the dune. From this analysis is concluded that there is no clear explanation other than that it is a result of the summation of smaller differences (in wave height, water depth, wave celerity etc.) between measurements and DUROSTA computations.

An important difference between the computations of the two tests is the almost constant maximum at approximately -0.33 m/s for test T05. During test T06 the maximum is clearly decreasing in time.

Based on both u_{ref} and u_m it can be stated that computed velocities are in general higher during T05 compared to test T06. It is therefore concluded that a larger wave period in DUROSTA also gives slightly larger undertow velocities. This tendency is however not as clearly observed in the measurements.

4.4 Sediment concentration model

In the sediment concentration model the vertical distribution of the time-averaged sediment concentration is determined. As described in Paragraph 2.4 the vertical distribution is dependent on several parameters i.e. the sediment concentration at the bottom, the fall velocity (grain size), the vertical mixing gradient and the reference mixing coefficient at the bed. In the analysis of the sediment concentration model, measured and computed concentration verticals are compared directly. Subsequently also bottom concentrations and depth averaged concentrations are analysed in more detail. The results are described in the following sections.

Performance based on measured verticals

The figures in Appendix C.2 and C.3 show measured sediment concentration verticals and the sediment concentration verticals computed by DUROSTA for tests T06 and T05. Comparison of the measured and computed verticals shows that DUROSTA underestimates the sediment concentrations almost systematically for test T06. Especially at locations closer to the dune (205-195 m) the differences are large. Because concentrations are much larger at these locations compared to locations further from the dune the effect on the sediment transport will here be much larger.

For the locations close to the dune (205 m and 200 m) the shapes of the concentration profiles agree quite well with the measurements. At 195 m and 190 m DUROSTA computes much more curved verticals than the measurements show and also the trends in time are not the same. Also at 185 m and 180 m the curvature computed by DUROSTA is much more pronounced. In contrast to the velocity verticals, the heights of the computed and measured sediment concentration verticals are comparable.

Also during test T05 the concentrations are underestimated significantly by DUROSTA at 205 m. Computed concentration verticals for tests T05 and T06 are comparable at this location. Measured concentrations are much higher for test T05, especially at the beginning of the test. The shape of the verticals at this location agrees again quite well. At 200 m the overall magnitude and shapes are computed relatively well too. At 195 m and 190 m DUROSTA overestimates the measurements but the shapes still agree well. At the locations 185 m and 180 m, DUROSTA underestimates the measurements again and for 185 m the vertical is much more curved than the measurements.

Especially for test T06 the shapes of computed verticals are significantly more curved than the measured verticals, mainly for locations further from the dune. The shape of the concentration profile in DUROSTA is controlled by the mixing coefficient and the fall velocity. The fall velocity is determined by the diameter of the sediment, which is assumed constant in the vertical by DUROSTA. In reality the particle size is graded, and mixing will lead to a vertical sorting of suspended material. Higher in the vertical the diameter is therefore relatively smaller. Van de Graaff (1988) states that this may result in higher concentrations close to the water level and lower concentrations close to the bed, compared to the case with a uniform distribution. In theory this would suggest that the verticals in the model would be less curved than in reality. This is however the opposite of what was concluded above. Another indication that this curvature should not be explained by the gradation of particle sizes is that the phenomenon was not observed in test T05, although the same sediment was used. The reason of the much more curved computed verticals should therefore probably be attributed to the distribution of the mixing coefficient in the vertical. Further research on this aspect is required.

Performance based on bottom concentration

In the previous section the overall magnitude of the verticals was compared visually. Another method for comparing the overall magnitude of the sediment concentration verticals is studying computed bottom concentrations and estimated measured bottom concentrations. DUROSTA determines first this bottom concentration for the overall magnitude of the vertical and uses afterwards the sediment mixing distribution and the fall velocity to determine the shape of the vertical. The bottom concentration is in this way the basis of the vertical and is therefore interesting to study in more detail.

Obviously bottom concentrations were not measured during the experiments. To make an estimation of the measured bottom concentration a least squares fit was applied to the measured concentrations using:

$$c = e^{Az+B} \tag{4.2}$$

From this fit a concentration at the bed level can be estimated (Van Rijn, 1993).

In Figure 4.5 computed and estimated bottom concentrations are presented for test T06 and test T05. The left plots show the bottom concentrations over the whole profile. It must be remarked that the output of DUROSTA is only given at the first measurement interval of each subtest. The measurements however are spread over each subtest. In general it can be stated that measurements further from the dune also take place later in the subtest. The DUROSTA graphs may therefore slightly overestimate the actual results. The right plots show how the computed and estimated bottom concentrations are correlated. The measurements in these plots can directly be compared with the computations.

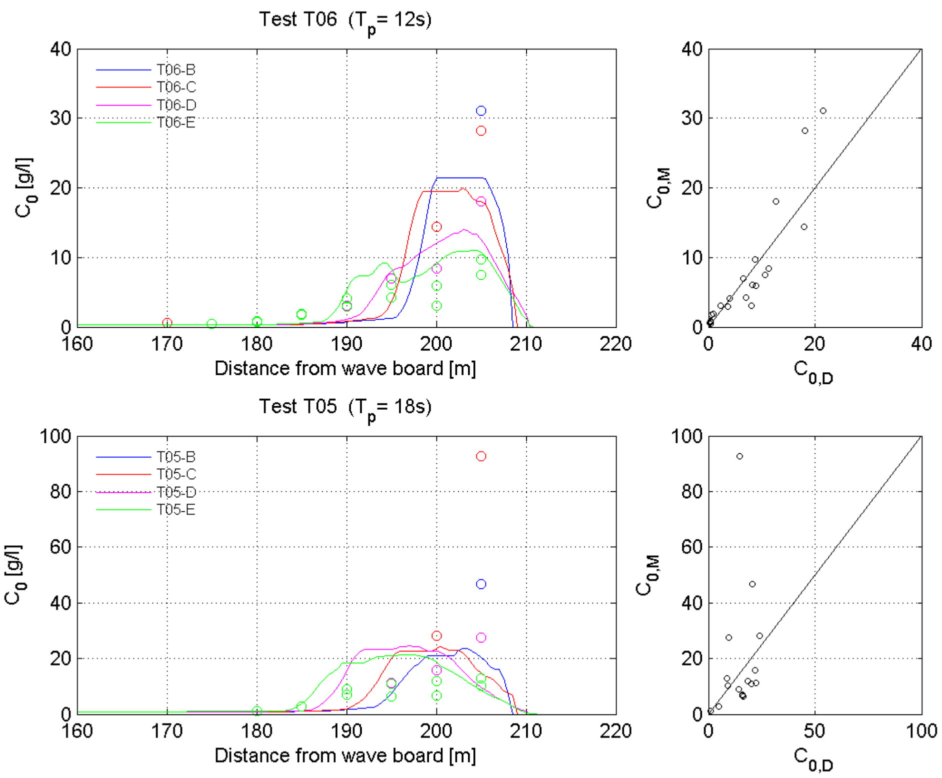


Figure 4.5 Bottom concentrations from measurements (dots) and DUROSTA (solid lines), test T06 (upper plots) and T05 (lower plots)

The trend of increasing concentrations towards the dune is observed for both measurements and computations. The measurements however show a far more gradual increase than the DUROSTA results; in the computations high concentrations are concentrated in a rather small area.

Another remarkable feature in the computations is that during test T05 the tops of the graphs remain on approximately the same level, around 20 g/l. The small variation in magnitude of the computed results for this test is also clearly observed in the correlation graph. This is in contrast to the results of test T06 where bottom concentrations are clearly decreasing in time. The variation in magnitude is much larger as well. The phenomenon of an almost constant maximum during test T05 was also observed in the analysis of depth averaged concentrations.

From the correlation graphs is concluded that the overall magnitude agrees in general quite well between the computations and measurements (especially for lower concentrations), although slightly overestimated by DUROSTA. Only at 205 m DUROSTA underestimates the concentrations significantly. Especially at the beginning of the tests (subtest A-D) the estimated measured bottom concentrations are much larger than the computed values for this location. The agreement for subtest E is however quite good for 205 m. It should however be noted that rather different conclusions were drawn from the visual comparison of the verticals in the previous section. This can be explained by the different shapes of the verticals.

Performance based on depth averaged concentration

As described in Paragraph 2.5 DUROSTA calculates the depth averaged, seaward directed sediment transport from multiplication of the velocity and concentration verticals. In this respect it might also be interesting to compare the depth averaged values of the measured and computed concentration verticals. Depth averaged concentrations are calculated for the measurements in the same way as described in Paragraph 3.2.4. The depth averaged concentrations for DUROSTA are also calculated from the computed verticals. Because DUROSTA computes the seaward directed transport from integration over the water depth until the mean wave trough level both measured and computed verticals are integrated over the water depth until the mean wave trough level.

The resulting depth averaged concentrations are shown in Figure 4.6. The squares represent the depth averaged values calculated from the DUROSTA verticals and the dots represent the depth averaged values of the measurements. Note the difference in the y-axis scale for both tests.

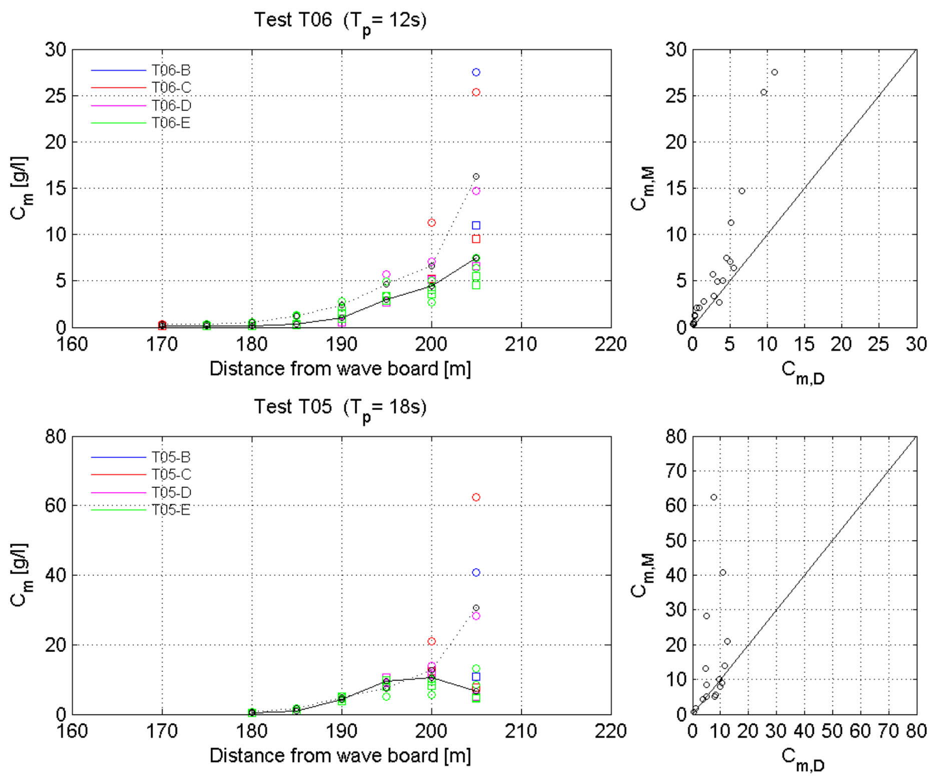


Figure 4.6 Depth averaged sediment concentrations from measurements (dots) and DUROSTA (squares), test T06 (upper plots) and T05 (lower plots)

From these figures is concluded that DUROSTA underestimates the depth averaged measurements especially at 205 m from the wave board. Further from the dune the results are again quite good.

In test T06 the mean concentrations of DUROSTA are increasing towards to dune, just like the measurements show. The range of the concentrations computed by DUROSTA is however much smaller (correlation graphs), this was also observed in the analysis of C_0.
For test T05 the same trend can also distinguished except for the results at 205 m from the wave board. These values are lower again in DUROSTA. This is remarkable since measurements show the opposite trend. It should be noted that based on C_0 DUROSTA overestimated the results for test T05 systematically except at 205 m. For C_m the agreement is however quite well at these locations. This difference can be explained by the shape of the verticals. Also for this test the range of sediment concentrations computed by DUROSTA is much smaller (correlation graphs) compared to the measurements, as was observed in the analysis of C_0 as well.

4.5 Cross-shore transport model

By multiplication of the time averaged velocities and concentrations DUROSTA calculates the depth averaged sediment transport. The sediment transport computed by DUROSTA is shown in Figure 4.7 and Figure 4.8 with the dashed lines. These lines represent the mean sediment transport over each subtest and are derived from averaging the transport at the beginning of two subsequent subtests. For example the red line (sediment transport for subtest B) is the mean of the initial transport of subtest B en subtest C.
The sediment transports in measurements are derived from the measured bed level change and from multiplication of measured flow velocities and sediment concentrations, see Paragraph 3.2.5. The solid line in the figures below represents the transport calculated from the measured bed level change. The dots show the transport calculated by multiplication of measured velocity and sediment concentration verticals.

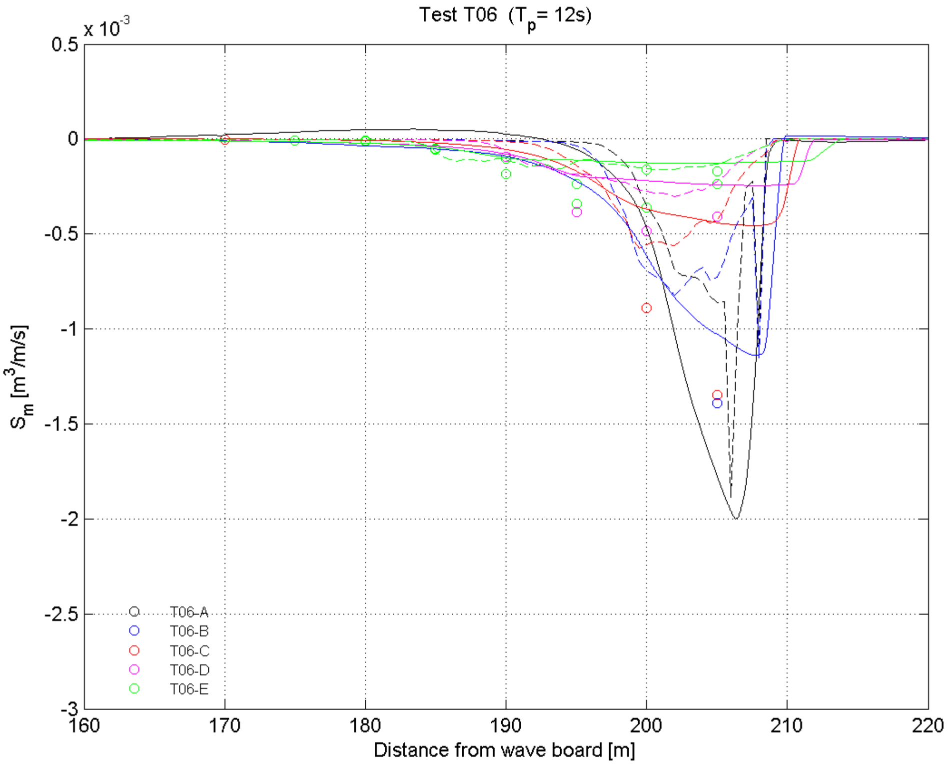


Figure 4.7 Sediment transport from verticals (dots), from bed level change (solid lines) and DUROSTA (dashed lines), test T06 (T_p=12s)

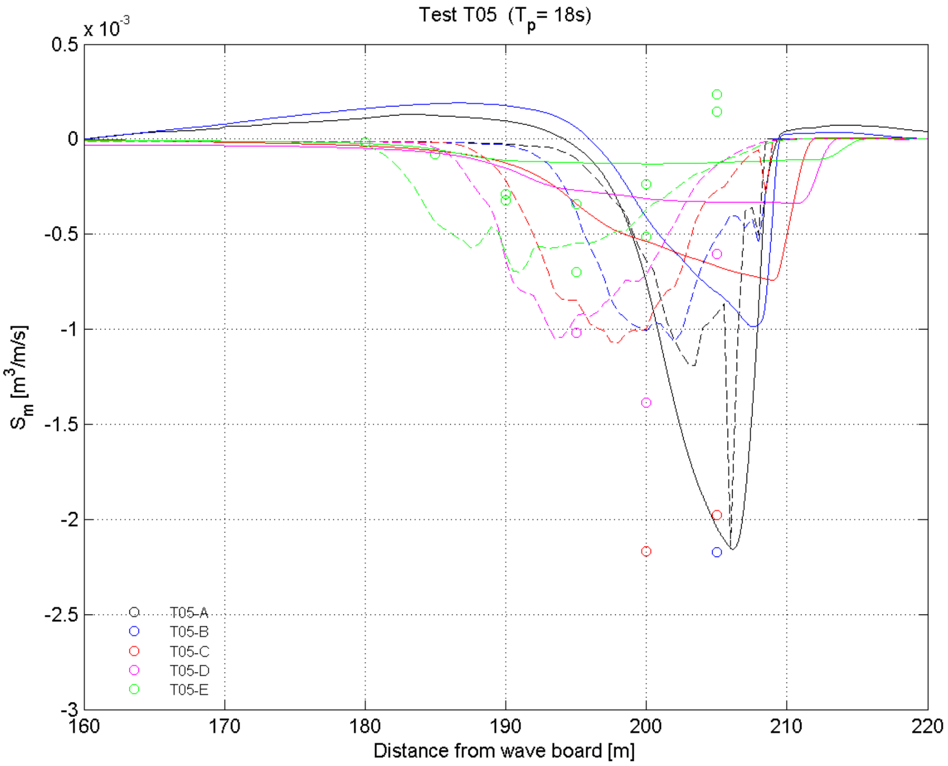


Figure 4.8 Sediment transport from verticals (dots), from bed level change (solid lines) and DUROSTA (dashed lines), test T05 (T_p=18s)

The most characteristic feature in the sediment transport lines from DUROSTA is that they are not as smooth as you would expect, especially the large spikes near the dune in subtest A and B are remarkable. Further analysis showed that the spikes near the dune decrease fast during the first time steps. Furthermore these irregularities and spikes are only visible in the sediment transport graphs and are probably smoothened by numerical smoothing in the bed level change model.

A clear difference in the trends between measurements and DUROSTA computations is the shifting direction of the maximum transport. In the measurements the maxima are logically shifting in the landward direction, however for the computations these maxima shift seaward. Related to this phenomenon is that erosion takes place between the computed maxima and the location of the dune face. Sedimentation only occurs much further from the dune, seaward from the maximum transports. Especially for test T05 during subtest B-E it seems that the profile is eroding quickly between 200 m and 210 m and sedimentation takes only place from approximately 200 m and more seaward. Sediment transport computed for test T05 is in general higher compared to test T06.

Compared to the transport calculated from the measured bed level change, the overall magnitude is rather well computed by DUROSTA for test T06, except for the erosion in front of the dune. For test T05 the results are however less good. Besides the fact that the top of the graph has shifted seaward much more compared to test T06, DUROSTA also overestimates the results especially for subtest D and E significantly. The seaward shifting maximum of the graph, with an almost constant value, was also observed in the analysis of both flow velocities and sediment concentrations.

Compared to the sediment transport derived from the verticals, transports computed by DUROSTA underestimate the measurements for test T06. This is also expected based on the systematic underestimation of the flow velocities and sediment concentrations for this test (Paragraph 4.3 and Paragraph 4.4). For test T05 DUROSTA also mainly underestimates the measurements, especially in the first part of the test and close to the dune. This was also expected based on the significant underestimation of the sediment concentrations near the dune. The transport calculated from these measured verticals are however less reliable than the transport calculated from the measured bed level change.

Some remarks about the relation between sediment transport and flow velocities and sediment concentrations are made. At 205 meter large differences between measurements and computations for both velocities and concentrations were observed. At this location DUROSTA significantly overestimated the measured velocities, whereas sediment concentrations were considerably underestimated, both with approximately a factor two. Although the reliability of the velocity measurements in questionable at these locations it may indicate that the computed high velocities compensate for computed low concentrations or the other way around, while in fact the sediment transport agrees again quite well at this location, especially for test T06.

4.6 Conclusions and interpretation

In the previous paragraphs the performance of the sub models in DUROSTA was studied, using measurement data from large scale model tests. This analysis especially focussed on the influence of the wave period in the model. In this paragraph, first the main conclusions from the analysis of the sub models are summarised. Based on these conclusions, some expectations about the integral performance of the DUROSTA model (Chapter 5) are described in the second part of this paragraph.

4.6.1 Conclusions

Wave propagation model

- The ENDEC-model, used for the computation of the wave height decay of short waves over the dune profile, performs well for default settings (i.e. γ = 0.85) in the near dune area. In the middle of the profile the agreement is less good, especially for test T05 (T_{prot}=18s).
- Both measurements and DUROSTA computations show a larger wave height over the entire profile in case of a larger wave period.
- Based on initial calculations, it is not expected that the wave period effect is caused by a larger computed wave height (w.r.t. measurements) in case of a larger wave period. This is in contrast to what earlier researches of Den Heijer (2005) and Steetzel (1993) stated.

Cross-shore flow model

- At deeper water the undertow velocities are in general underestimated by DUROSTA. Especially for test T06 (T_{prot}=12s) DUROSTA underestimates the measurements up to a factor 2. An important difference between the computations of the two tests is the almost constant maximum at approximately -0.33 m/s for test T05 (T_{prot}=18s). During test T06 (T_{prot}=12s) the maximum is clearly decreasing in time.

- In general computed flow velocities are higher for test T05 (T_{prot}=18s) compared to test T06 (T_{prot}=12s). This tendency is not observed this clearly in the measurements.

Sediment concentration model

- DUROSTA underestimates the depth averaged concentrations systematically for test T06 (T_{prot}=12s). For test T05 (T_{prot}=18s) DUROSTA only underestimates the measurements significantly at 205 m.
- The concentrations computed by DUROSTA are concentrated in a very small range, whereas the measurements show a much larger spreading of concentrations, especially in the direction of the dune.
- Computed sediment concentrations are in general higher for test T05 (T_{prot}=18s). The larger wave period results in larger concentrations (factor 2 at maximum). This is also observed in the measurements.

Cross-shore transport model

- Compared to the transport calculated from the measured bed level change, the overall magnitude is rather well computed by DUROSTA for test T06 (T_{prot}=12s). For test T05 (T_{prot}=18s) the agreement is less good. DUROSTA overestimates the results especially for subtest D and E significantly.
- A characteristic difference in trends between measured and computed sediment transport is the shifting direction of the maximum transport. In the measurements, maxima are shifting landward, whereas computed maximum transports shift seaward. Related to this phenomenon is the erosion in front of the dune. Especially in test T05 (T_{prot}=18s) during subtest B-E it seems that the profile is eroding quickly between 200 m and 210 m. Sedimentation only takes place seaward of approximately 200 m.
- Sediment transport computed for test T05 (T_{prot}=18s) is in general higher compared to test T06 (T_{prot}=12s).

4.6.2 Interpretation

In this chapter a lot of insight was gained in the performance of the sub models in DUROSTA. In the analysis of the sub models only initial calculations were used. In this way it is not possible to study the capability of the model to predict the profile development in time. In the next chapter this last aspect is studied by examining the integral performance of DUROSTA. Based on the current insight the following predictions about the morfodynamic performance of the complete DUROSTA model are made:

- Trends in flow velocities and sediment concentrations are in general well simulated by the sub models in DUROSTA. However, flow velocities and sediment concentrations are mainly underestimated by the corresponding DUROSTA sub models. Based on only these physical processes it is thus expected that in morphodynamic computations also the amount of dune erosion will be underestimated.

- A larger wave period influences both the computed flow velocities and the computed sediment concentrations. Flow velocities increase slightly with an increasing wave period, but especially the sediment concentrations increase significantly. It is therefore expected that a clear wave period effect is observed in the morphodynamic computations as well.

5 Integral performance of DUROSTA

In the previous chapter insight was gained in the individual performance of the DUROSTA sub models with initial computations. Initial calculations could not be used to study the capability of the model to predict the profile development in time. In this chapter the performance of DUROSTA is examined for full test simulations using the data analysis described in the Paragraph 3.2. An important part of the analysis of these morphodynamic computations is again the influence of the wave period on the model results.

Paragraph 5.1 discusses the results of the morphodynamic computations for different wave periods (same test conditions as used in Chapter 4). Based on the individual performance of the sub models, in Chapter 4 some expectations were formulated regarding the integral performance of DUROSTA. The results of the morphodynamic computations are evaluated with these expected results. The evaluation of DUROSTA is divided in assessing the performance of the model in general and assessing the performance regarding the influence of the wave period. It is concluded that, apart from the physical processes represented by the sub models, other processes are included in the DUROSTA model which have an important influence on the prediction of dune erosion with DUROSTA. In Paragraph 5.2 different components and factors in DUROSTA are analysed in more detail to examine which additional processes are important in modelling dune erosion with DUROSTA. Paragraph 5.3 describes a sensitivity analysis of the wave period effect. It is studied how the wave period effect in dune erosion is influenced by other physical parameters.

5.1 Full test simulations

In this paragraph full test simulations are carried out to study the performance of the complete DUROSTA model in predicting dune erosion during a storm surge for different wave periods. First the performance of the different sub models is examined for test averaged values. This implies that for both test T06 (T_p=12s) and test T05 (T_p=18s) mean wave heights, flow velocities and sediment concentrations are studied for the complete duration of each test (6 hours). Secondly the profile development in time is analysed in these 6 hours. In the last part of this paragraph results of the full test simulations are evaluated and compared to the expected results based on the analysis of the sub models in Chapter 4.

All simulations are performed for default settings, see Appendix A.

5.1.1 Performance of sub models

In Chapter 4 sub models of DUROSTA were analysed with initial computations. From this analysis conclusions were drawn regarding the performance of the sub models. It is possible that these results were dominated by spin-up effects. Therefore in this paragraph the performance of the sub models is analysed for full test simulations. For the wave height, flow velocities and sediment concentrations test averaged values (6 hours) are determined.

Wave propagation model

Figure 5.1 shows the test averaged root mean square wave height for only high frequency waves. For the measurements (dots) test averaged values are deduced from the average wave height of each subtest (A-E). These values are weighted to include the length of the intervals. Test averaged values for DUROSTA are obtained by averaging output with a time interval of 6 minutes.

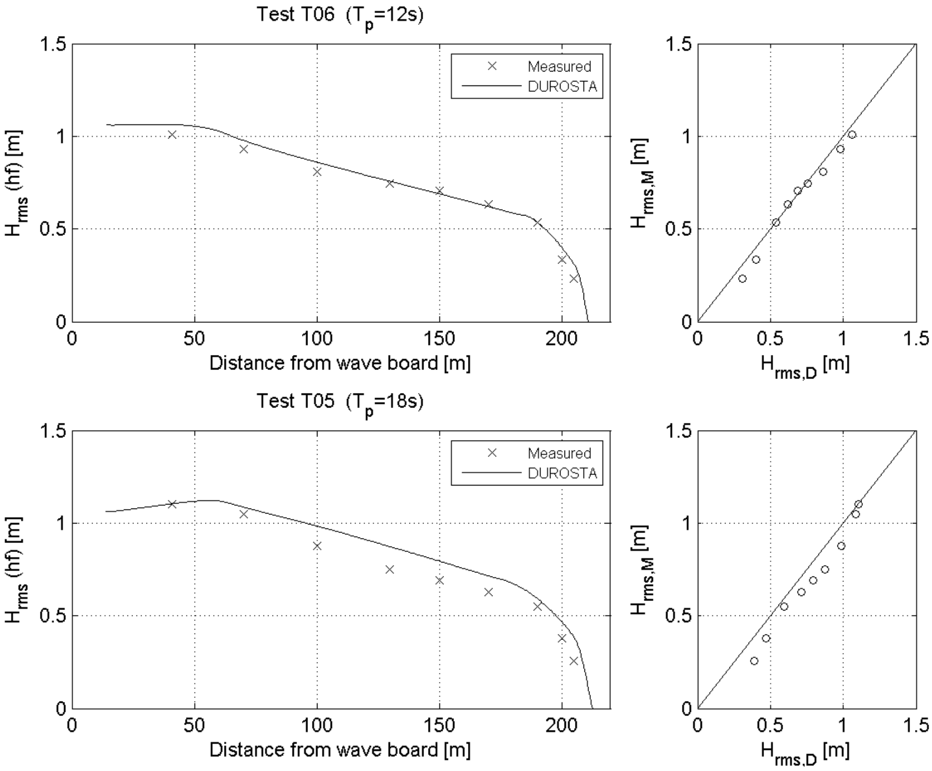


Figure 5.1 Test averaged, high frequency, root mean square wave height from measurements (dots) and computations (solid line) for test T06 (upper plot) and test T05 (lower plot).

From this figure is concluded that for the test averaged wave heights are well simulated for test T06. Near the dune an overestimation of the measurements is observed in the order of 20-25 percent. For test T05 the results are less good. Especially in the middle of the profile, DUROSTA overestimates the measurements significantly. Near the dune, DUROSTA overestimates the results with respectively 20 and 50 percent at the last two locations. As will be seen in Paragraph 5.1.2 DUROSTA computes a larger water depth in front of the dune compared to the measurements. A larger depth allows a larger wave height which explains the overestimated wave height near the dune.

For an increasing wave period the computed wave height is clearly larger over the entire profile. For the measurements this depends on the cross-shore location, but is in general wave heights are also slightly larger for a larger wave period. The same conclusions were drawn from the initial calculations.

It is concluded that for full test simulations the ENDEC-model overestimates the measurements significantly in the near dune area.

Cross-shore flow velocity model

Figure 5.2 shows the test averaged undertow velocities. From the measurements test averaged velocities are obtained by averaging all the flow velocity measurements for each location of the shallow water frame along the profile. Test averaged values for DUROSTA are obtained by averaging output with a time interval of 6 minutes.

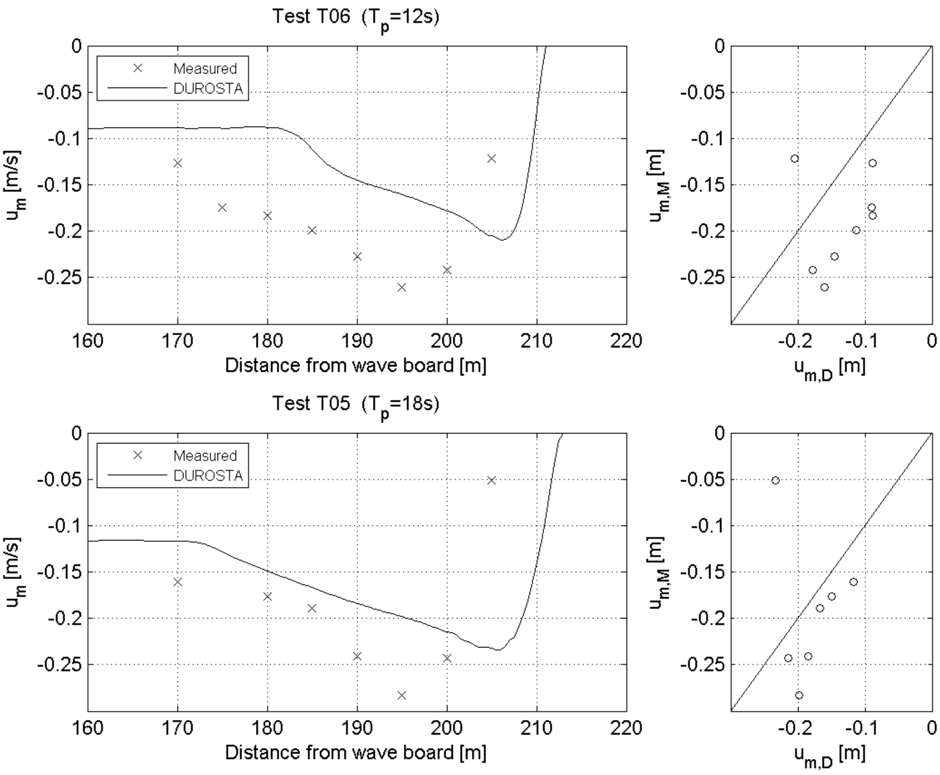


Figure 5.2 Test averaged, undertow velocities from measurements (dots) and computations (solid line) for test T06 (upper plot) and test T05 (lower plot).

In this figure is observed that spatial trends in velocities agree well for both tests; however DUROSTA underestimates the measurements significantly. Especially for test T06 the underestimation is for certain points even a factor 2. This was also observed in the initial calculations of Paragraph 4.3. At 205 meter from the wave board DUROSTA overestimates the measurements considerably. This may be explained the fact that very few measurements were used in the vertical were large velocities gradients occur. The measurements are probably not representative for the actual velocities at this location.

In the DUROSTA results, larger flow velocities are observed with an increasing wave period. This was also observed in Paragraph 4.3.

Sediment concentration model

In Figure 5.3 test averaged concentrations are shown for both tests T06 and T05. For the measurements test averaged values are obtained from averaging all sediment concentration measurements for each location of the shallow water frame along the profile. DUROSTA is not able to gives depth averaged concentrations as output. At several locations along the profile depth averaged values were therefore calculated based on exported verticals (with a time interval of 6 minutes).

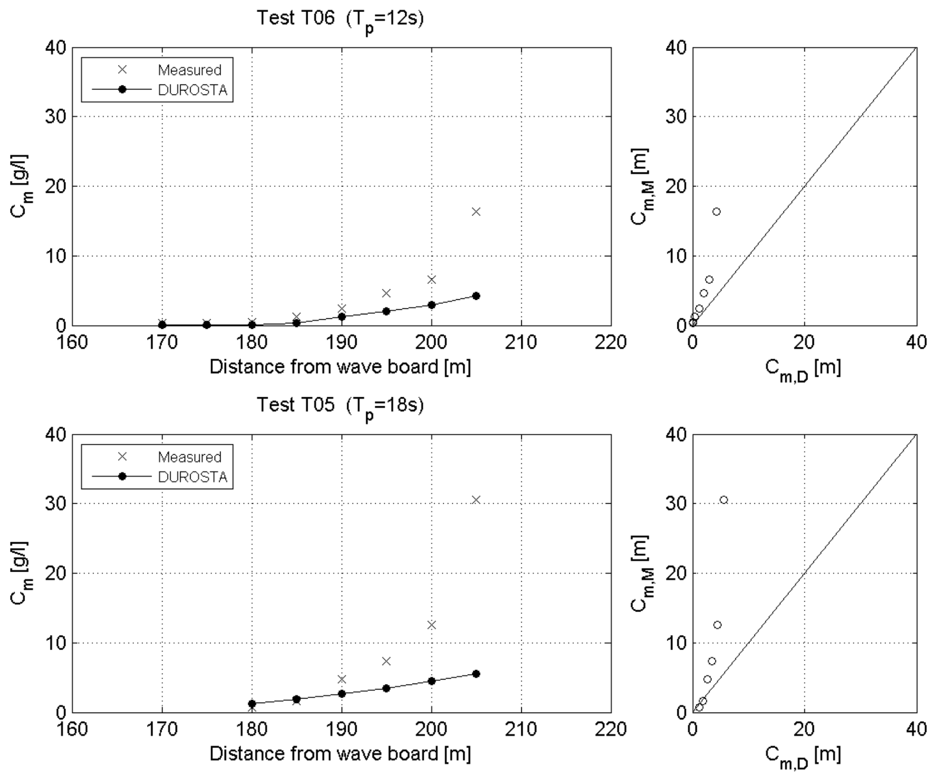


Figure 5.3 Test averaged, sediment concentrations from measurements (dots) and computations (solid line) for test T06 (upper plot) and test T05 (lower plot).

From the figure can be concluded that trends between measurements and DUROSTA agree well, however DUROSTA underestimates the measured sediment concentration significantly between 190 and 205 meter from the wave board. This is remarkable since the wave height was significantly overestimated, close to the dune. The concentrations in DUROSTA are concentrated in a very small range, whereas the measurements show a far more drastic increase in the direction of the dune. This underestimation of the concentrations was also observed in the initial computations for both tests.

5.1.2 Profile development in time

For test T06 and test T05 the development of erosion profiles and corresponding erosion volumes are computed. The computed erosion profiles of both tests are shown in the left plots in Figure 5.4 with the solid lines. The dash-dot lines represent the measured profiles during the physical model tests. The right plots present the development of erosion volume in time. The erosion volume is defined here as the total amount of eroded material above and below the mean water level.

The computed erosion volumes are not multiplied with the recommended factor 1.12 to include porosity effects (Steetzel, 1993). The model is calibrated at the under water profile for wave periods lower than or equal to 12 seconds. In this case erosion volumes were underestimated which was explained by porosity differences between sand eroding the dune and the deposited sand in front of the dune. Steetzel (1993) therefore recommends multiplying the erosion volumes with a factor 1.12. As was seen in Paragraph 3.2.1, during the physical model tests used in this research porosity differences were opposite from the tests used by Steetzel (1993). It is therefore decided not to use the factor 1.12 in this study.

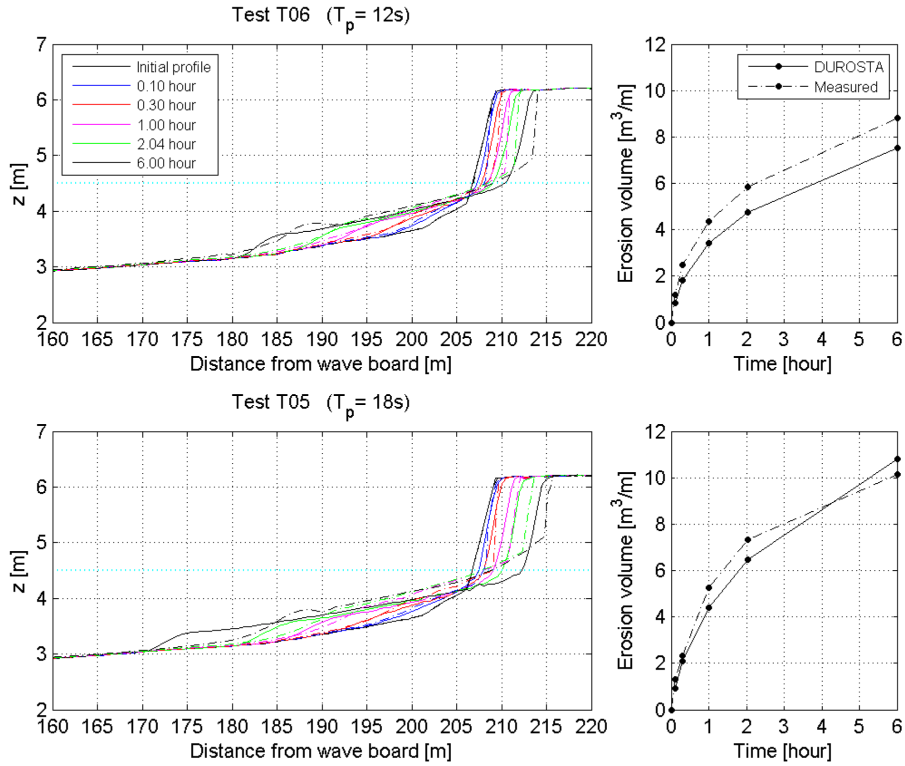


Figure 5.4 Measured (dashed line) and computed (solid line) erosion profiles and volumes for test T06 and test T05

For test T06 the location of the computed dune top agrees quite well with the location of the measured dune top during the whole test. Also the length of the deposition area corresponds well. The main differences between measured and computed profiles are the location of the dune foot and the slope of the dune face. During the experiments the dune foot moves up until above the mean water level. In the computations the dune foot is almost located at the mean water level. The slope of the dune face is steeper in the measurements, which results in a more landward located waterline. The computed profile lies slightly lower than the measured profile for this test. DUROSTA underestimates the erosion volume with respectively 20 and 13 percent after 2.04 and 6 hours. If the recommended factor of 1.12 (Steetzel, 1993) was applied to the computed erosion volumes the results get significantly better.

For test T05 the differences between measured and computed bottom profiles have increased. In the computations the location of the dune top is predicted too much seaward (during a large part of the test) and the bottom profile lies much lower, especially between 205 m and 212 m. A large amount of erosion has occurred below the waterline. The length of the deposition area is considerably larger compared to the measurements. The plot of the erosion volume development shows quite good net results. If the recommended factor of 1.12 was applied DUROSTA would overestimate the measured volumes significantly, especially after 6 hours.

An important difference for test T05 is that in reality the depth decreases rather fast, DUROSTA however calculates a slower decreasing depth in front of the dune face. This is caused by the fact that the dune foot in DUROSTA is located near the waterline, while the measured dune foot moves up even above the waterline. In this way the height of the dune face does not decrease in time in the computations, in contrast to the trend the measurements show. The slow decreasing depth may also have a large influence on a potential equilibrium situation.

Regarding the wave period effect on dune erosion it is concluded that the height of the profile increases for a larger wave period in the physical model tests, the computed profile lies however lower. For DUROSTA the length of deposition area increases significantly whereas for the measurements only a small increase is observed.
The wave period effect can be expressed in terms of relative increase in erosion volume. This relative increase in volumes is shown in Table 5.1 for both 2.04 and 6.0 hours (model scale).

Table 5.1 Wave period effect expressed in relative increase in erosion volumes

	2.04 hour	6.0 hour
Measurements	25 %	15 %
DUROSTA	35 %	43 %

From this table is concluded that the wave period effect is much larger for DUROSTA compared to the measurements. As was observed in the figures this is caused by the much lower laying profile. In measurements the wave period effect decreases in time, whereas in DUROSTA computations the effect is increasing at least in the first 6.0 hours.

5.1.3 Evaluation

It is concluded that generally the same trends can be distinguished in the analysis of sub models for full test simulations as in case of the initial calculations. Although the wave height is overestimated close to the dune, large underestimations in flow velocities and sediment concentrations occur. In this respect it is remarkable that the profile development and erosion volumes are still quite well computed by DUROSTA. Apparently other processes/factors are present in the model, which initiate additional sediment transports and are thus important in simulating dune erosion with DUROSTA. The transport correction factor, described in Paragraph 2.5.1, is such a factor. It is applied to compensate for inadequacies in the transport model and increases the calculated transport from the flow velocities and sediment transports with a factor 1.6. However, based on the velocities and concentrations a much larger underestimation of the erosion volumes is expected. Other possibilities this phenomenon can be attributed to are the method of modelling the transport over the dry profile, numerical smoothing, slope correction factor and the grid size. These parameters will be further studied in Paragraph 5.2.

In both the measurements of the physical model test and the full test simulations a wave period effect is clearly observed. From the analysis of the sub models was concluded that the wave period effect is mainly caused by increasing sediment concentrations and thus more suspension of sediment rather than by higher undertow velocities. This was also observed in the measurements. A remarkable feature is the simulated dune foot location in case of a wave period of 18 seconds. DUROSTA predicts the dune foot location much lower compared to the measurements. Although the location of the dune face is underestimated, the low position of the dune foot (compared to the measurements) results in higher computed than measured erosion volumes. The location of the dune foot is related to the extrapolation of transport over the dry profile. Since this phenomenon is important in modelling dune erosion with a larger wave period it is further described in the next paragraph.

5.2 Other important processes

From Paragraph 5.1 was concluded that, besides the physical processes represented by the sub models, other processes have to be included in DUROSTA which have a large influence on predicting dune erosion. In this paragraph several components and factors which may have an important influence on the results are studied in more detail, i.e. the method of modelling the sediment transport over the dry profile, numerical smoothing, slope correction factor, grid size and the location of the dune foot.

5.2.1 Modelling of sediment transport over the dry profile

In this paragraph the approach of modelling the sediment transport over the dry profile is examined. In DUROSTA this sediment transport is determined by extrapolation of transport over the dry area (Paragraph 2.6). The influence of extrapolation method on the model results is studied. Since this method is relatively complicated it is interesting to study how other, more transparent, extrapolation methods perform when used in the DUROSTA model. Important parameters in the extrapolation are the significant run-up and the location at a ¼ wavelength from the waterline (Paragraph 2.6.1). The influence of these parameters is studied as well.

Extrapolation method

A specific DUROSTA component is the method of extrapolation of sediment transport over the dry profile. For a detailed description of the method of extrapolation see Paragraph 2.6. Since this method is relatively complicated it is interesting to investigate how other, more transparent, extrapolation methods perform when used in the DUROSTA model. The following three methods are studied and compared with the default DUROSTA method of extrapolation:

- Horizontal extrapolation
- Vertical extrapolation
- No extrapolation

First a short description of these methods is given. Afterwards the results for applying different extrapolation methods in the DUROSTA model are discussed.

Horizontal extrapolation
In the case of a horizontal extrapolation method, extrapolation is executed in the horizontal direction, see Figure 5.5. The reduction factor which is used to determine the transport over the dry profile (based on a reference transport) depends on the *relative run-up location*. This implies that the reduction factor at a certain point of the dry profile depends on the relation between the horizontal location of that point and the horizontal location of the significant run-up and a ¼ of the local wavelength. Equation (2.39) from Paragraph 2.6.2 is then simply replaced by:

$$S(x)=S^*\left[1-\left(\frac{x-x_{sw}}{x_s-x_{sw}}\right)\right] \tag{5.1}$$

in which:

S^*	time-averaged, depth-integrated sediment transport per unit width in last wet computation point	[m^3/m^1/s]
x_{sw}	a quarter of the local wavelength from the waterline	[m]
x_s	location of significant wave run-up	[m]

The variables used in Equation (5.1) are visually explained by Figure 5.5.

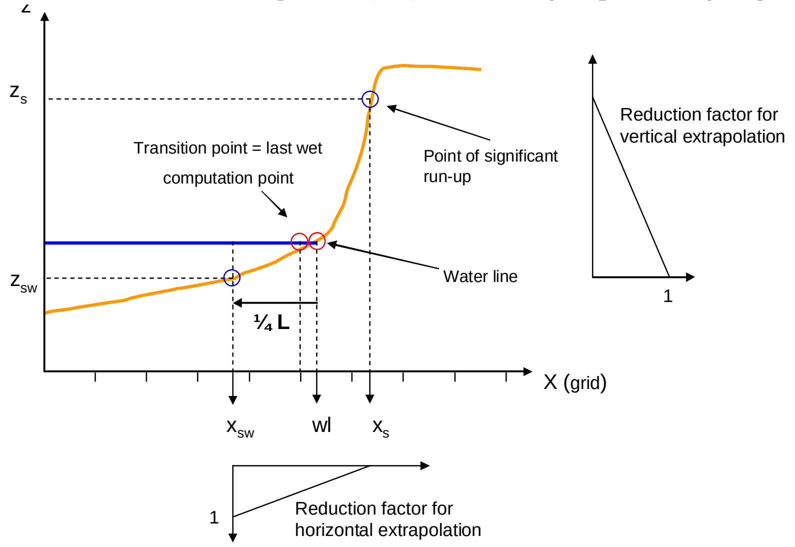


Figure 5.5 Explanation of variables used in horizontal and vertical extrapolation

Vertical extrapolation

In the case of the vertical extrapolation method, extrapolation is executed in the vertical direction, see Figure 5.5. In vertical extrapolation the reduction factor depends on the *relative run-up height*. In contrast to the horizontal method the local height of the dune is taken into account and as a result the extrapolated profile shifts landward with a fixed shape. For vertical extrapolation Equation (2.39) is simply replaced by:

$$S(x)=S^*\left[1-\left(\frac{z(x)-z_{sw}}{z_s-z_{sw}}\right)\right] \tag{5.2}$$

in which:

z_{sw}	bed level at quarter of the local wavelength from the waterline	[m]
z_s	significant wave run-up above the mean water level	[m]

The relative run up height is also used as a parameter in the default extrapolation method in DUROSTA. Difference is however that in DUROSTA this relative run up height is used as a parameter in a more elaborate function to determine the reduction factor, see Paragraph 2.6.2. This more complicated function was added to include the fact that sediment transport is larger at the dune foot (compared to the upper part of the dune face). In this way the dune front will initially get steeper, before moving backward with a fixed shape.

No extrapolation

No extrapolation implies that a reduction factor of zero is applied for sediment transport over the dry profile. The dune face should therefore not retreat and no sediment is supplied from the dune. To meet the sediment demand of the beach and foreshore, this should in theory lead to an erosion pit in front of the dune.

Results

In Figure 5.6 the erosion profiles after six hours model time are shown for the different extrapolation methods.

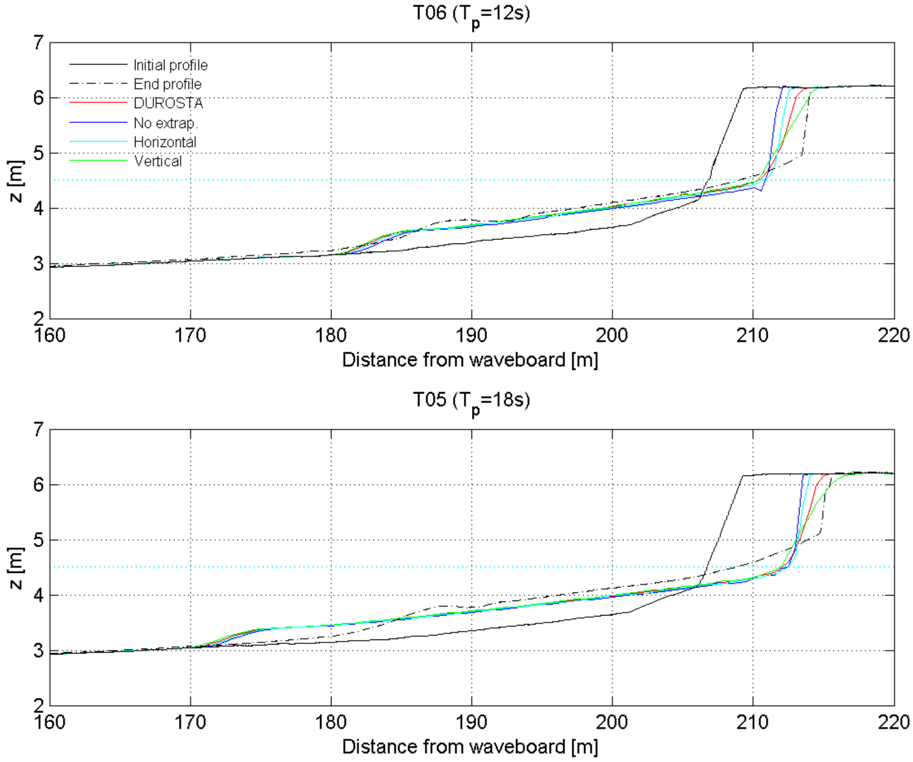


Figure 5.6 Profile development for different extrapolation methods after six hours for test T06 (upper plot) and T05 (lower plot)

As can be observed in the figure, different extrapolation methods do generally not influence the under water profile, but mainly the dry profile. Only when no extrapolation is applied, some erosion is observed in front of the dune face.

Differences between the four methods of extrapolation are thus especially observed in terms of shape of the dune face. The profiles of computations with no extrapolation are comparable with the results of the horizontal extrapolation. For both methods the dune face is rather steep, however in the latter case more erosion is observed. For vertical and the DUROSTA extrapolation the dune face is less steep. Based on the measurements the steep dune face is much more realistic. The location of the dune top is however much better computed when vertical extrapolation is applied.

Although differences do occur, the influence on the profile development is relatively small. From this it is concluded that the relative run-up is important in modelling the shape of the retreating dune face. It is possible that in these computations the run-up always exceeds the dune top because of the extreme hydraulic conditions. To check whether the conclusion also holds for computations where the run-up does not continuously exceed the dune top, an additional comparison is performed with other flume experiments, see Appendix D.1. Also for these tests the differences between the extrapolation methods is small. From this can be concluded that relative run-up is indeed an important parameter to model the shape of the retreating the dune face.

The results of the different extrapolation methods are discussed in more detail in the next part.

It is remarkable that in the case of no extrapolation the dune face is still retreating and no erosion pit occurs in front of the dune. Since no sediment transport is extrapolated over the dry profile, and thus no sediment should be supplied from the dune, this is not expected. It is possible that some bed level changes occur because of the central numerical scheme (LAX-scheme) used in the bed level change model. This scheme enables bed level change in the gridcel after the last point in which sediment transport is calculated (the last wet computation point). However the changes are very large and can therefore not be explained only by this numerical scheme. Also from this is concluded that an additional process is included in the model that originates transport from the dry profile, even without extrapolation. At this point it is most likely that this can be attributed to numerical smoothing and/or some of the transport calibration factors (described in Paragraph 2.5.1). This aspect is further studied in Paragraph 5.2.2.

The steep profile computed by horizontal extrapolation is comparable with the profile calculated with no extrapolation. For no extrapolation such a steep profile can be expected, however for horizontal extrapolation it is not so straightforward. It can be explained by the fact that the reduction factor is computed from a ¼ of the local wavelength from the waterline until the wave run-up height, see Figure 5.7.

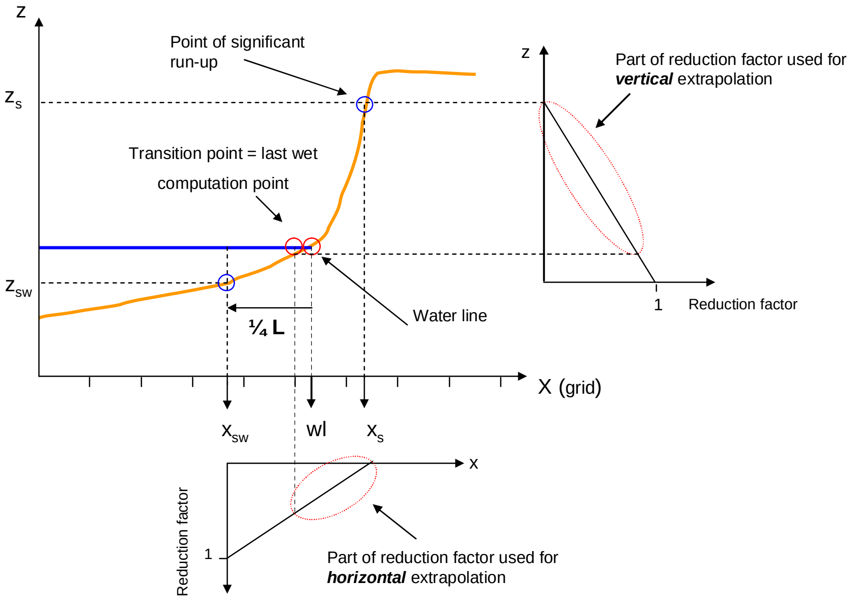


Figure 5.7 Reduction factor for horizontal (below) and vertical extrapolation (right)

From ¼ wavelength the reduction factor is already decreasing, however the actual extrapolation of sediment transport starts not until the last wet gridcel. At this point the reduction factor has decreased significantly and only a small part is used for the actual extrapolation. The figure also shows that the decrease of the reduction factor is much smaller for vertical extrapolation. It may also explain why the difference between horizontal and no extrapolation is even smaller for larger wave periods. The wavelength is in this case larger and the reduction factor decreases even more until the actual point of extrapolation.

The default DUROSTA extrapolation shows indeed relatively more erosion lower in the vertical compared to the vertical extrapolation. The dune face computed by the latter method is much flatter than was measured, and is therefore regarded as less realistic. For both methods the dune face retreats with a fixed shape.

¼ wavelength

DUROSTA uses the local depth at a certain distance from the water line for the determination of the relative wave run-up (for a more detailed description see Paragraph 2.6). In default computations this distance is equal to ¼ of the local wavelength. As explained in Figure 5.7 this distance is not only used for the determination of the relative run-up but also for the start of the reduction factor. In this respect it seems logical to change this ¼ wavelength to zero. In this way reduction of the sediment transport over the dry profile starts at the last wet computing point (transition point). In this paragraph the sensitivity of the model regarding this distance is examined. To this end it had been varied with ½ L, 1/10 L and 1/100 L. The resulting erosion profiles are shown in Figure 5.8 for a wave period of 12 seconds. The results for other extrapolation methods and a larger wave period are given in Appendix D.2.

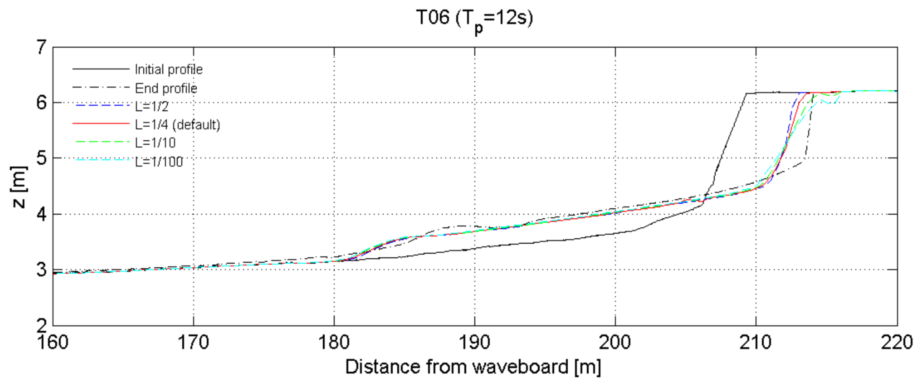


Figure 5.8 Influence of the ¼ wavelength on erosion profile

Enlarging the distance makes the dune face slightly steeper, which can be explained by the phenomenon described in Figure 5.7. If the distance is decreased the shape of the dune face is influenced very much, in this case also an irregular shape of the dune face is computed. This is probably due to the fact that the distance is also used in the relative wave run-up.

Significant run-up

The significant wave run-up is used in the determination of the reduction factor, through the relative wave run-up (for a more detailed description see Paragraph 2.6). The influence of the significant wave run-up is assessed by using an additional factor (F_{ZS}) to modify the run-up as follows:

$$z_s = F_{zs} 0.5 T_p \sqrt{g H_s} \tan \beta \qquad (5.3)$$

The default value of F_{ZS} is 1. In this sensitivity analysis the factor is varied between 0.5 and 1.2. The influence of the significant run-up on the erosion volumes after 2.04 hours is shown in Figure 5.9.

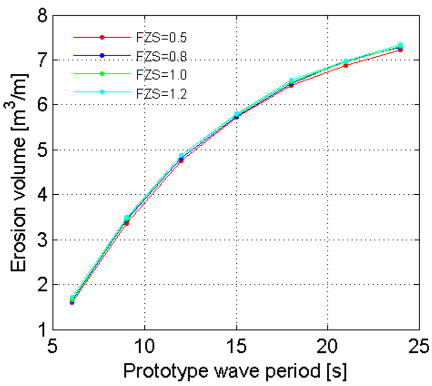


Figure 5.9 Influence of significant run-up on erosion volume as a function of the wave period.

From these graphs is concluded that the significant run-up has no significant influence on the amount of erosion. This is remarkable since the run-up was assumed to be the governing physical parameter in the calculation of the reduction factor used for extrapolation of sediment transport over the dry profile (Paragraph 2.6). More research on this subject is required.

5.2.2 Numerical smoothing and bed slope effects

In Paragraph 5.1.3 was concluded that processes are present in the DUROSTA model which initiate additional transport on top of the transports computed from flow velocities and sediment concentrations. The previous paragraph showed that in case of no extrapolation still a large amount of sediment was taken from the dune, which also indicates that an additional process is included in the model that initiate transport from the dry profile. At this point it is likely that additional transports are caused by numerical smoothing of the bed level changes (Paragraph 2.7) and/or slope factors as described in Paragraph 2.5.1. Therefore the sensitivity of the model for these factors is studied in more detail. In the next sections the influence of the following factors on the model results are discussed:

- Numerical smoothing factor γ
- Slope correction factor K_{sl}
- Swash factor K_{sw}

The influence of each of these factors on the erosion profile and erosion volumes is investigated by setting them to zero. Also the combined effect of the factors is studied. The analysis in this paragraph focuses on the results for no extrapolation and default DUROSTA extrapolation. Likewise only a wave period of 12 seconds is shown in this paragraph, since the qualitative effects are the same for different wave periods.

Numerical smoothing (γ)

The numerical smoothing factor is applied in the bed level change model to smoothen sharp transitions in the computed bed level (Paragraph 2.7). This is especially important in the vicinity of the dune where there is a steep slope and large gradients occur in sediment transport. The default value of γ is 0.05.

Figure 5.10 shows the erosion profiles (after 6 hours model time) when the numerical smoothing is applied (solid lines) and is not applied (dashed lines) in the bed level change model. The blue lines represent the results in case of no extrapolation. The red lines give the situation using the default DUROSTA extrapolation. The results for all extrapolation methods and a larger wave period are shown in Appendix D.3.

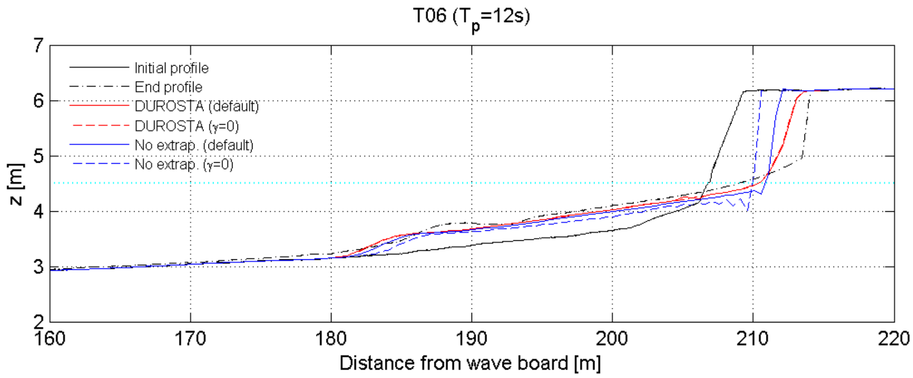


Figure 5.10 Influence of numerical smoothing on erosion profile for no extrapolation (blue line) and DUROSTA extrapolation (red line)

From this figure is concluded that the numerical smoothing coefficient mainly influences the computations with no extrapolation. A saw-tooth shape bottom profile is distinguished in front of the dune face. Numerical smoothing is in principle applied to overcome this problem, so in this case the computations benefit indeed from this additional factor. It is however remarkable that numerical smoothing has nearly no influence for default DUROSTA extrapolation. The shape of the erosion profile is practically the same compared to the standard case. For no extrapolation the deposition area lays (slightly) lower.

Table 5.2 shows the difference in erosion volumes. For no extrapolation the erosion volume has decreased with more than 23 percent. The smoothing factor induces for no extrapolation thus a significant extra bed level change. For DUROSTA this is only 1 percent.

Table 5.2 Influence of numerical smoothing on erosion volumes

Test T06 (T_p=12s) Erosion volume [m^3/m]	No extrapolation	DUROSTA extrapolation
Default	6.8	7.7
γ = 0	5.2	7.6

Slope factor (K_{sl})

To include slope effects on the sediment transports in the model a slope factor is applied as follows (see also Paragraph 2.5.1):

$$S_x^{'}(i) = \left[1 + K_{sl}\left(\frac{\Delta z_b}{\Delta x}\right)\right] S_x(\mathrm{i}) \Bigg|_{i=1}^{i=last\ wet\ gridcel} \qquad (5.4)$$

This factor is only applied over the wet profile. The default value of K_{sl} is 4.0.

Figure 5.11 shows the erosion profiles (after 6 hours model time) when the slope correction factor is applied (solid lines) and is not applied (dashed lines) in the transport model. The blue lines represent the results in case of no extrapolation. The red lines give the situation using the default DUROSTA extrapolation. The results for all extrapolation methods and a larger wave period are shown in Appendix D.3

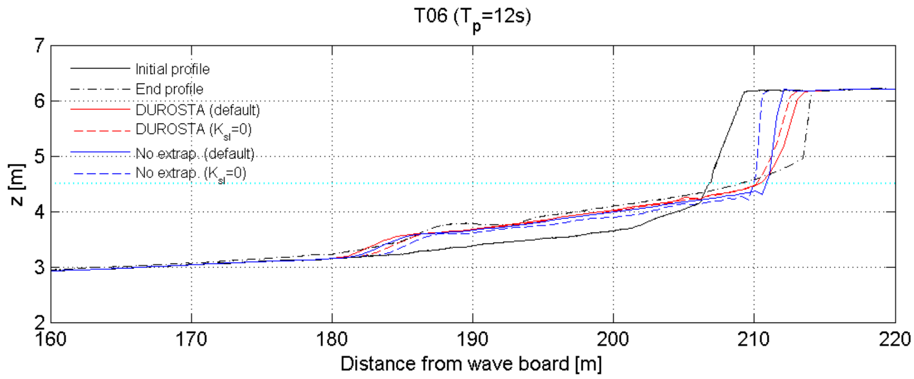


Figure 5.11 Influence of the slope factor on erosion profile for no extrapolation (blue line) and DUROSTA extrapolation (red line)

From this figure is concluded that the slope factor mainly influences the location of the dune front for both extrapolation methods. The dune front has retreated less compared to the reference (default) case. This results in a decrease in erosion volume of respectively 26 and 12 percent for no extrapolation and DUROSTA extrapolation, see Table 5.3.

Table 5.3 Influence of slope factor on erosion volumes

Test T06 (T_p=12s) Erosion volume [m^3/m]	No extrapolation	DUROSTA extrapolation
Default	6.8	7.7
K_{sl} = 0	5.0	6.8

Swash factor (K_{sw})

Besides the slope factor an additional factor is applied in the model to included slope effects, this is the swash factor. The swash factor is basically used in the same way as the slope factor. Only difference is that a factor 4 and the local wave height over water depth ration are added. For a more detailed description see Paragraph 2.5.1.

The swash factor is also used as a slope factor as follows:

$$S_x^{"}(i) = \left[1 + 4 * K_{sw} \frac{H_{rms}}{h}\left(\frac{\Delta z_b}{\Delta x}\right)\right] S_x^{'}(\mathrm{i}) \Bigg|_{i=2}^{i=last\ wet\ gridcel} \quad (5.5)$$

This factor is only applied over the wet profile. The default value of K_{sw} is 2.0.

Figure 5.12 shows the erosion profiles (after 6 hours model time) when the swash factor is applied (solid lines) and is not applied (dashed lines). The blue lines represent the results in case of no extrapolation. The red lines give the situation using the default DUROSTA extrapolation. The results for all extrapolation methods and a larger wave period are shown in Appendix D.3

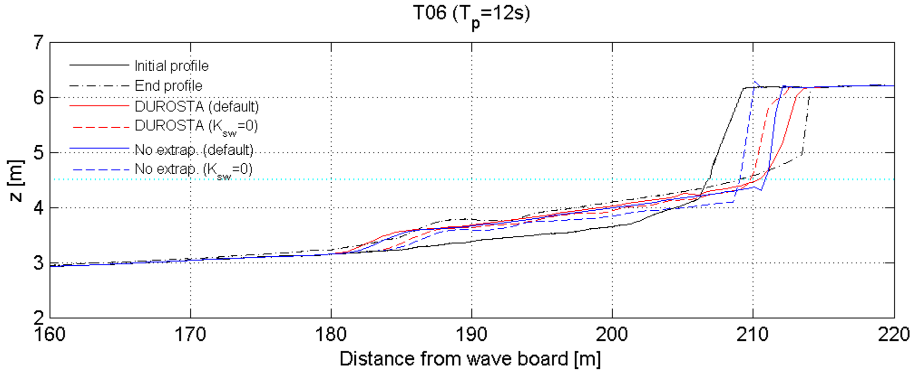


Figure 5.12 Influence of the swash factor on erosion profile for no extrapolation (blue line) and DUROSTA extrapolation (red line)

The figure shows that significant less erosion of the dune takes place for both methods in case the swash factor is not applied. In the deposition area changes are relatively small; the deposition area lies lower and is also more irregular compared with the default case. The dune face however retreats much less for both methods, which results in a decrease in erosion volume of 47 percent for no extrapolation and 27 percent for DUROSTA extrapolation, see Table 5.4.

Table 5.4 Influence of swash factor on erosion volumes

Test T06 (T_p=12s) Erosion volume [m^3/m]	No extrapolation	DUROSTA extrapolation
Default	6.8	7.7
K_{SW}=0	4.0	5.6

It should be noted that applying K_{sw}=1 in the model makes the results already much better, see Appendix D.4.

Combined effects

In the previous parts it was observed that the influence of the slope and swash factor on the amount of dune erosion is significant. In this part the combined effect of these parameters are studied.

Figure 5.13 shows the erosion profiles (after 6 hours model time) when both the slope and the swash factor are set to zero. The blue lines represent the results in case of no extrapolation. The red lines give the situation using the default DUROSTA extrapolation.

The results for all extrapolation methods and a larger wave period are shown in Appendix D.3

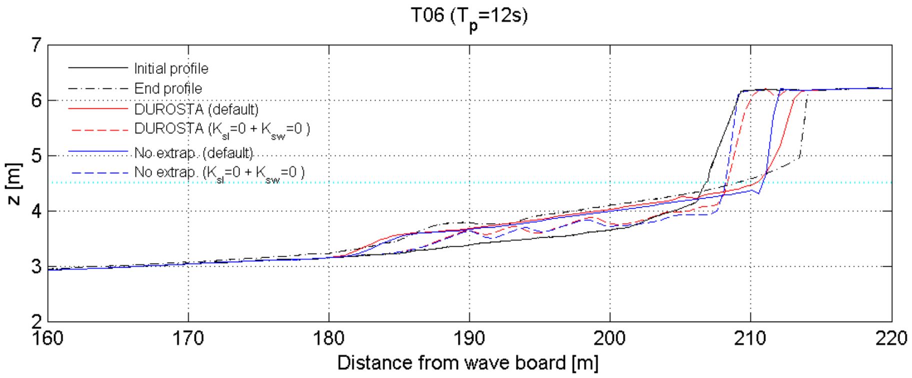


Figure 5.13 Influence of the combined effect of slope and swash factor on erosion profile for no extrapolation (blue line) and DUROSTA extrapolation (red line)

The figure shows that the combined influence of the factors is very large. The retreat of the dune front is minimal and almost the same for both methods. The deposition area is very irregular and located much lower compared to the default case. Also the dune foot lies much lower.

From Table 5.5 is concluded that the erosion volumes are reduced with 60 percent for both extrapolation methods.

Table 5.5 Influence of combined effect of the slope and swash factor on erosion volumes

Test T06 (T_p=12s) Erosion volume [m^3/m]	No extrapolation	DUROSTA extrapolation
Default	6.8	7.7
K_{SW}+K_{SL}=0	2.7	3.1

Figure 5.14 shows the erosion profiles (after 6 hours model time) when the numerical smoothing is set to zero as well. The blue lines represent the results in case of no extrapolation. The red lines give the situation using the default DUROSTA extrapolation. The results for all extrapolation methods and a larger wave period are shown in Appendix D.3

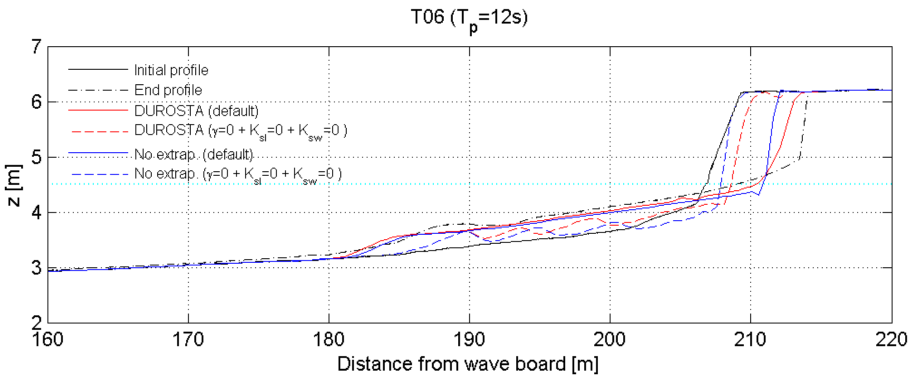


Figure 5.14 Influence of combined effect of numerical smoothing and the slope and swash factor on erosion profile for no extrapolation (blue line) and DUROSTA extrapolation (red line)

For DUROSTA no significant influence is observed compared with the previous case. For no extrapolation the dune face again retreats slightly less but a small amount of erosion is still visible above the waterline. In theory no erosion is expected in this case, since all factors are set to zero. Probably because of the central numerical scheme (LAX-scheme) some bed level changes are still computed.

Table 5.6 shows that the erosion volumes have indeed decreased again for no extrapolation, with 66 percent of the default case.

Table 5.6 Influence of combined effect of numerical smoothing and the slope and swash factor on erosion volumes

Test T06 (T_p=12s) Erosion volume [m^3/m]	No extrapolation	DUROSTA extrapolation
Default	6.8	7.7
$K_{SW}+K_{SL}+\gamma=0$	2.3	3.2

It must be noted that the influence of the slope factors on the dune erosion process predicted by DUROSTA is very large. From this analysis is concluded that 60 percent of the sediment transport in DUROSTA is created by the slope factors. This is remarkable since the DUROSTA model is a process based model which is based on the principle of computing transports by using flow velocities and sediment concentrations. The large effect of the slope factors on the sediment transports is therefore questionable.

5.2.3 Grid size

Especially in the transition zone between the wet and dry profile the grid size is most likely to be important. Therefore the influence of the grid size on the profile development is studied.
Until now a constant grid size of 0.50 m was applied. In this sensitivity analysis the sensitivity of the model is studied for a grid size of 0.25 m and 1.00 meter. The results are shown in Figure 5.15 for both cases. In Appendix D.5 the resulting profiles after 6 hours are shown for all extrapolation methods and a wave period of 18 seconds.

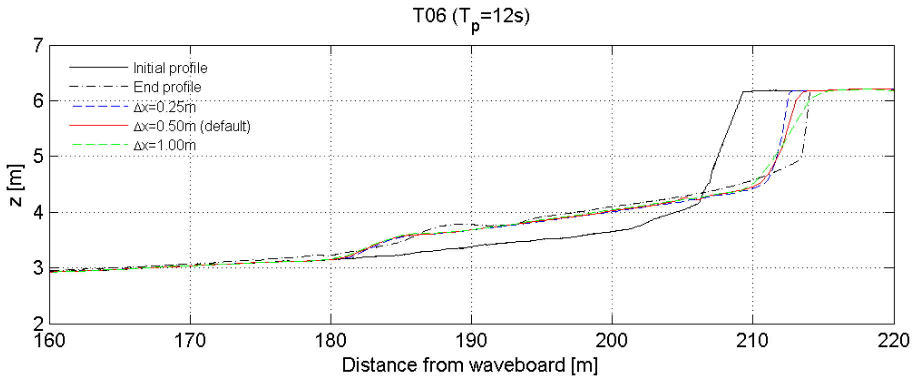


Figure 5.15 Influence of the grid size on erosion profile

From the figures is concluded that the grid size mainly influences the shape of the dune face and not the under water profile. The dune face gets steeper with a smaller grid size, which results in a smaller amount of erosion.

5.2.4 Dune foot location

In the full test simulations of test T05 it was observed that the bed level in front of the dune was located much lower compared to the measurements. This intention of the model to simulate a much lower laying bed level in front of the dune was actually already observed in the analysis of the sub-models with initial calculations. The computations in this analysis were performed with a (interpolated) measured bottom profile. Sediment transport was then calculated in such way that immediately erosion took place in front of the dune. Apparently the model searches to a kind of equilibrium which makes the initial transport right in front of the dune foot eroding in order to lower the imposed (higher) profile. This conclusion is substantiated by Paragraph 5.1.6 where the influence of the initial profile is examined.

This phenomenon can be explained by the fact that in DUROSTA sediment is extrapolated from the last wet gridcel, which is always fixed near the water line (Paragraph 2.6). The computations executed in the analysis of the sub models were initial calculations with a (interpolated) measured bottom profile. Especially in the last subtests of an experiment the measured dune foot lies much higher than the waterline (Figure 5.16). While in DUROSTA sediment transport over the dry profile is extrapolated from the last wet gridcel, significant erosion takes place between this point and the measured dune foot (and also seaward from the extrapolation point). This process continues until the extrapolation point and the dune foot are both located near the water line. This aspect is visually explained in the Figure 5.16.

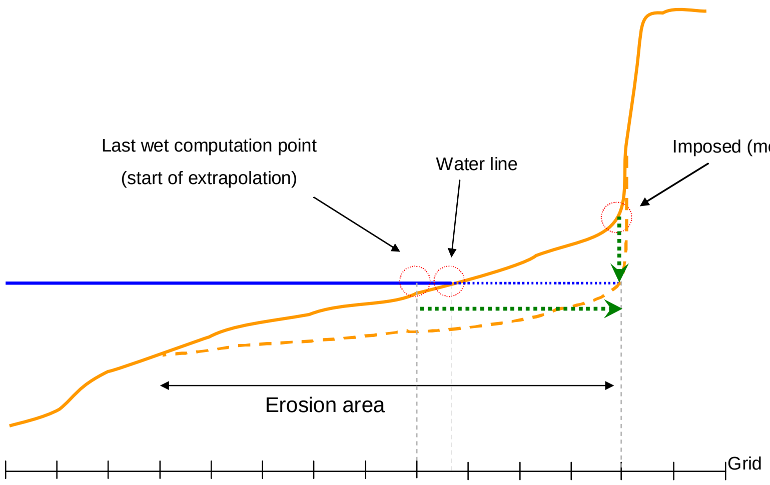


Figure 5.16 Forcing of simulated dune foot location in DUROSTA

It can be concluded that the extrapolation method gives unrealistic results regarding the location of the dune foot for simulations with higher wave periods. In reality the dune foot moves up to above the water level. Because the point of extrapolation in DUROSTA implicitly forces the dune foot to be located near the water line, this is not possible in DUROSTA simulations.

5.3 Sensitivity of the wave period effect

The objective of this study is to examine the performance of DUROSTA taking into account the influence of the wave period. Besides the wave period obviously also other physical parameters influence the capability of the model to simulate dune erosion. In this section a sensitivity analysis is performed to get a better insight in the influence of the main physical parameters on the computations. The analysis focuses on the sensitivity of the different parameters in relation to the wave period. It is studied how the wave period effect on dune erosion is influenced by certain other parameters. Physical parameters used as input for the model computations are; water level, wave height, breaker index and grain size and initial profile. In the next paragraphs the sensitivity of the model for these five parameters is examined.

5.3.1 Water level

In default computations a water level of 4.5 meter above the flume bottom was applied. The water level during the storm surge is assumed at NAP+5m in prototype which is 0.83 m above NAP on model scale. If it is assumed that NAP is approximately equal to still water level, the increase in mean water level due to the astronomic tide and storm surge is then 0.83 m. In this sensitivity analysis this additional increase in water level is varied with 25 percent, which results in water levels of 4.30 m and 4.70 m above the flume bottom. Computations are performed for a large range of wave periods en the resulting influence on the erosion volume is shown in Figure 5.17. The resulting erosion profiles after six hours are shown in Appendix E.1.

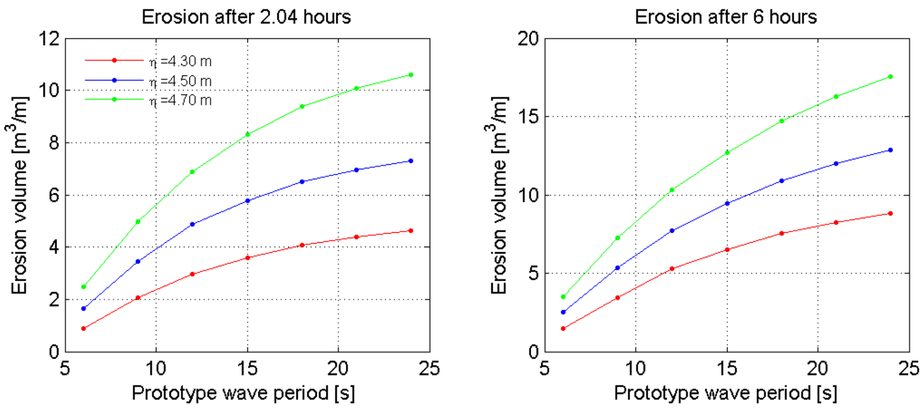


Figure 5.17 Influence of water level on erosion volumes. Erosion volumes are shown after 2.04 (left) and 6 hours (right) as a function of the wave period.

With an increasing water level the location of the dune foot becomes higher as well as the under water bed profile. The dune face retreat increases but the shape of the erosion profile is not influenced by the water level. It is noted that also in the existing empirical model, which is used to assess the safety of the dune coast in the Netherlands, the water level does not influence the shape of the erosion profile.

A change of 25 percent in the water level (above mean sea level) gives an additional erosion volume of approximately 30 to 40 percent, depending on the moment in time. This relative effect is approximately the same for the whole range of wave periods. The relative wave period effect is thus not affected by water level variations. The net amount of dune erosion increases however fast with an increasing wave period and water level. This is also expected since the maximum wave height, the driving force in a dune erosion model, is directly influenced by the water depth. The erosion volume seems to be proportional with the change in water level.

5.3.2 Wave height

In default computations a significant wave height of 1.5 m was applied. In this sensitivity analysis the wave height is varied with 33 percent, which results in a significant wave height of 1.0 and 2.0 meters. Computations are performed for a large range of wave periods; the resulting influence on the erosion volume is shown in Figure 5.18. The resulting erosion profiles after six hours are shown in Appendix E.2. In the left plot also lines of equal wave steepness are shown. It is remarked that in these plots only waves with a wave period larger than or equal to 12 seconds have a realistic steepness. For lower wave periods the steepness gets unrealistically high (s_0>>0.05).

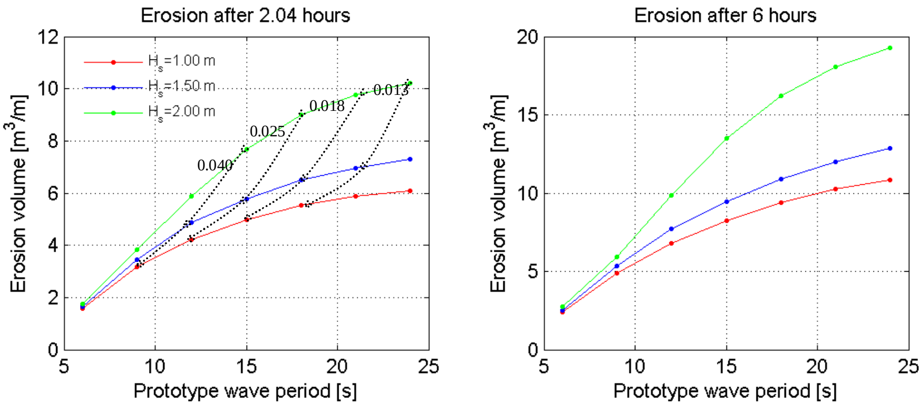


Figure 5.18 Influence of wave height on erosion volumes. Erosion volumes are shown after 2.04 (left) and 6 hours (right) as a function of the wave period.

It can clearly be observed that the wave height is a very important factor in predicting dune erosion and the wave period effect is highly influenced by the wave height. In case of a wave period of 24 seconds, a 33 percent increase in wave height gives an increase in erosion volume of approximately 40 percent. An increase of 33 percent with a wave period of 12 seconds only gives an increase in erosion volume of approximately 20 percent. The erosion volume is clearly not proportional with the change in wave height.

5.3.3 Breaker index

The main purpose of the breaker index is determining the maximum allowable wave height in the wave propagation model (Paragraph 2.2). Besides the wave propagation model also the cross-shore flow model and the sediment concentration model use the breaker index in the determination of the reference mixing coefficient, mixing gradient and the bottom concentration (see Paragraph 2.3 and 2.4). The breaker index was one of the main calibration parameters in the calibration of the model. It is therefore expected the influence of the breaker index on the model results is significant.

In DUROSTA a default value of 0.85 is used for the computations. In the sensitivity analysis of this parameter, gamma is varied between 0.6 and 0.9. Also the option of using the breaker index according to Battjes and Stive (1985) and Ruessink *et al*. (2003) is studied. Battjes and Stive state that the breaker index is dependent on the deep water wave steepness s_0:

$$\gamma = 0.5 + 0.4\tanh(33 s_0) \qquad (5.6)$$

According to this method the breaker index decreases with an increasing wave period.

Ruessink *et al*. state that the breaker index is dependent on the product of the wave number ($k = 2\pi / L$) and the local depth (h):

$$\gamma = 0.76kh + 0.29 \quad (5.7)$$

The resulting erosion volumes for the different breaker indices are shown in Figure 5.19.

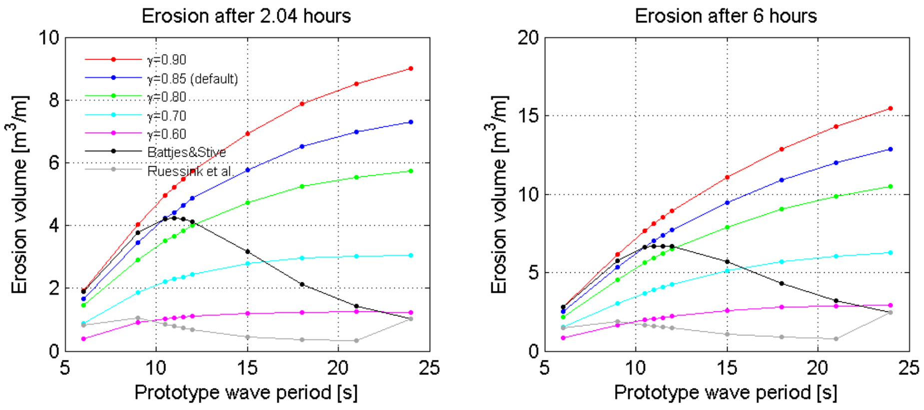


Figure 5.19 Influence of breaker index on erosion volumes. Erosion volumes are shown after 2.04 (left) and 6 hours (right) as a function of the prototype wave period.

Variation of the breaker index has a large influence on the amount of erosion. For a low breaker indices (e.g. 0.6 and 0.7), the influence of the wave period is very small. For larger breaker indices the amount of erosion increases more quickly with an increasing wave period.

For both variable breaker indices, i.e. the breaker index according to Battjes and Stive (1985) and the breaker index of Ruessink *et al.* (2003), the results are rather different.

By applying Ruessink *et al.* (2003) almost no erosion is computed. The breaker index calculated by this method predicts a much lower wave height over the profile compared to the measurements, see Appendix E.3. Since the wave height is a very important parameter in determining dune erosion with DUROSTA it is expected that this wave height is to low to cause any significant erosion.

For Battjes and Stive (1985) a maximum erosion volume occurs at a prototype wave period of approximately 11 seconds (depending on moment in time). For wave periods larger than 11 seconds the wave period effect is reversed, i.e. the erosion volume decreases with an increasing period. This trend was not observed in the measurements is therefore also not expected. Since the breaker index is included in the model in several ways, it is not entirely clear what causes this phenomenon. One explanation may be that the wave steepness decreases for a larger wave period. According to Battjes and Stive (1985) the breaker index decreases with decreasing wave steepness as well. This results in a lower maximum wave height with an increasing wave period, see also Appendix E.3. Since the wave height is a very important parameter in determining dune erosion with DUROSTA it is possible that this lower computed wave height results in less erosion. However as was described before, the breaker index is also included in other parts of the model. Next to the effect on the maximum wave height, the breaker index also directly influences the mixing coefficient and mixing gradient in both the flow velocity and sediment concentration model. Additionally the reference sediment concentration (C_0) in the concentration model (Paragraph 2.4) is also dependent on the breaker index. Further research on this aspect is recommended.

From this analysis is concluded that DUROSTA is very sensitive to the breaker index. This was also to be expected since the breaker index directly determines the maximum wave height, which is the driving force of the model. Further it is remarkable that the capability of DUROSTA to simulate dune erosion decreases significantly when the variable breaker indices of Ruessink *et al.* (2003) and Battjes and Stive (1985) are applied. This indicates again that the model is indeed calibrated very well for a breaker index of 0.85.

5.3.4 Grain size

In default computations a grain size of 200 µm was applied. In the sensitivity analysis of the grain size it was varied with 25 percent of this standard value. The results are shown in Figure 5.20.

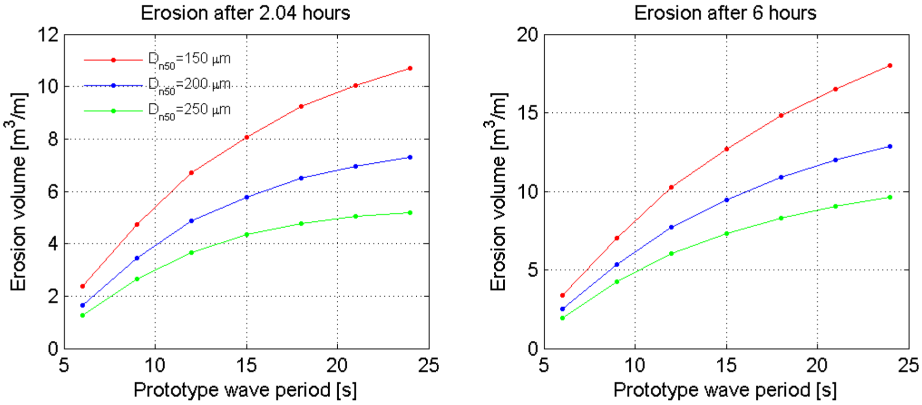


Figure 5.20 Influence of grain size on erosion volumes. Erosion volumes are shown after 2.04 (left) and 6 hours (right) as a function of the wave period.

Variation of the grain size only influences the amount of erosion, not the shape of erosion profiles (Appendix E.4). The graphs show that the wave period effect gets relatively larger for smaller grain size. For example with a wave period of 24 seconds a decrease in grain size with 25 percent results in an erosion increase of 50 percent. Whereas with a wave period of 10 seconds this is only approximately 35 percent. The erosion volume is not proportional with the change in grain size.

5.3.5 Initial profile

The sensitivity of profile development for the initial profile is studied in two ways. First four measured dune profiles after respectively subtests A, B, C and D in test T06 en T05 are imposed. It is examined what the influence of using these profiles is on the end results. Secondly a totally different dune profile is applied, namely the begin profile of test T08 (see Paragraph 3.1.3). This test contains a relative narrow (extra) dune and a so called sand pit at relatively deep water. It is studied whether DUROSTA is also capable of simulating the erosion process with these begin profiles.

Profiles from model tests

While the erosion processes are very fast in the beginning of the experiments it might be possible that DUROSTA is not able to simulate this accurately enough. It is therefore interesting to examine the influence of the initial profile on the profile development. Four additional simulations where performed for each test. In these simulations measured profiles after respectively subtests A, B, C and D are imposed as initial profiles. The resulting profile development for these four simulations is shown in Appendix E.5. From these pictures it can be concluded that the influence of the initial profile on the end profile is rather small. Even in the case of imposing the measured end profile of subtest D, which is located much more landward than the computed profile after D, the influence on the end profile is almost negligible. The profile shapes are practically the same and also the location of the dune face differs only very little. From the graphs, it also becomes clear that DUROSTA searches first for a kind of standard profile shape. Especially for test T05 this profile is a much lower laying profile than the measured profile and was already related to the location of the extrapolation point near the water line (Paragraph 5.2.4). This new profile is reached by initial large erosion in front of the dune, which was already seen in the transport graphs in Paragraph 4.5. When the profile has reached this 'equilibrium' shape, the profile development is the same as with other initial profiles.

In Figure 5.21 the influence of the initial profile development of the erosion volume is shown for both tests. Note the difference in scale of the y-axis. The black line shows the erosion development as computed with the initial profile used in the measurements and can be used as a reference. The colored lines show the erosion development after applying the different measured profiles as initial profile in DUROSTA. Also in these graphs the high initial transports can be distinguished by the fast increase of erosion in the beginning of the simulations (colored lines). After a while the colored lines get parallel to the black line which indicates that the 'equilibrium' shape has been reached and the transport rate is the same as in the reference case.

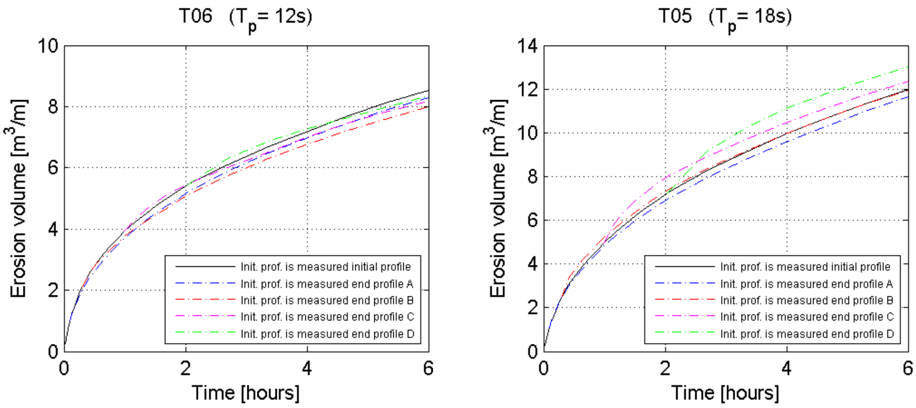


Figure 5.21 Influence of initial profile on development of computed erosion volumes test T06 and test T05

Initial profile of test T08

In the large scale experiments described, in Chapter 3, one of the tests examines the influence of the initial profile on the dune erosion development. In this test T08 the initial profile contains a relative narrow (extra) dune and a so called sand pit at relatively deep water. Here it is studied whether DUROSTA is also capable of simulating the erosion process with these kind of begin profiles. The results for the first 6.0 hours are shown in the Figure 5.22. The left plot shows the development of the erosion profile, whereas the right gives the development of the erosion volume in time.

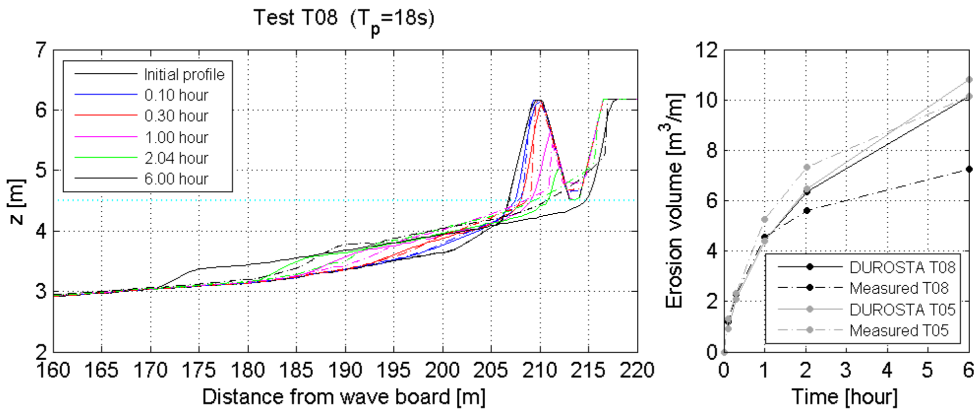


Figure 5.22 Influence of initial profile of test T08; measured profiles are represented by the dash-dot line, DUROSTA profiles are represented by solid lines

In general the dune erosion process is simulated rather well. Until the first hour the erosion volumes are almost exactly the same. Differences in profile occur however. The retreat of the dune face is faster during the experiments whereas DUROSTA predicts a lower laying profile. During the experiments the small dune has therefore eroded faster. The location of the dune face after 6 hours is almost the same. Again it is observed that the profile in front of the dune is much lower. This is the same as in test T05 because these simulations are both with a large wave period. For the computations also the end volumes of test T05 and T08 differ only with 1 m^3/m, where the erosion volume for T05 is the largest. In the measurements this difference is much larger. Also in this case the erosion volume is larger during test T05. Apparently the longer shallow foreshore, which occurs when the first dune has eroded, slows down the erosion rate significantly. The dune face has however for both the measurements and the computations further retreated for test T08.

At 70 m from the wave board a sand pit is located. During the experiment the edges of the pit smoothened and the sand pit moved little in the direction of the dune. During the last subtest half of the sand pit filled up (Figure 5.23).

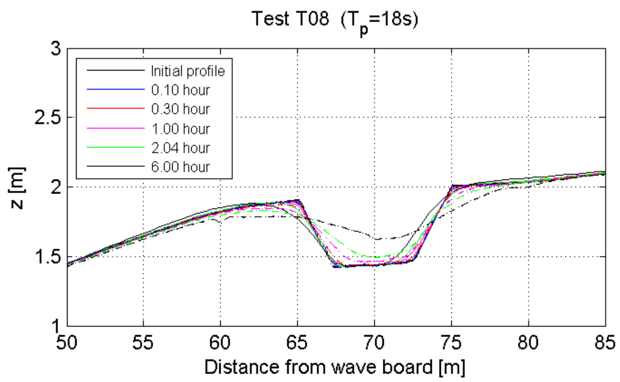


Figure 5.23 Influence of initial profile of test T08, sand pit; measured profiles are represented by the dash-dot line, DUROSTA profiles are represented by solid lines

In the DUROSTA computations no significant development of the pit is observed in the first four subtests. Only in the last test the pit has moved a bit seaward, so in the opposite direction as was found in the measurements. This can be explained by the fact that in the model mainly offshore transport is taken into account.

5.4 Conclusions

In this paragraph the main conclusions from this chapter are summarised.

Full test simulations

- The ENDEC-model overestimates the test averaged (6 hour) wave heights significantly in the near dune area for both test T06 (T_p=12s) and test T05 (T_p=18s).
- Spatial trends in flow velocities agree well for both test T06 (T_p=12s) and test T05 (T_p=18s). DUROSTA underestimates the measurements significantly, especially for test T06 (T_p=12s) the underestimation is at certain locations even a factor 2.
- Spatial trends in sediment concentrations agree well for both test T06 (T_p=12s) and test T05 (T_p=18s). DUROSTA underestimates the measured sediment concentration significantly, especially close to the dune between 190 and 205 meter from the wave board.
- For both test T06 (T_p=12s) and test T05 (T_p=18s) the profile development in the first 6 hours is simulated well. The dune face retreat is however underestimated. For test T06 (T_p=12s) this results in an underestimation of the erosion volumes. Despite the fact that the dune face retreat is also underestimated by DUROSTA, the erosion volumes are predicted rather well.
- In both the measurements of the physical model test a wave period effect is clearly observed in terms of location of the dune crest and erosion volumes. After 2.04 hours the relative increase in erosion volume is 25 percent in the physical model tests and 35 percent in DUROSTA computations. After 6 hours the wave period effect has decreased to 15 percent in the measurements and increased to 43 percent in the DUROSTA computations.

Other important processes

- The influence of different extrapolation methods, i.e no extrapolation, horizontal extrapolation, vertical extrapolation and the default DUROSTA extrapolation, on the profile development in DUROSTA is relatively small. From this is concluded that the significant run-up is important in modelling the shape of the retreating dune face.
- DUROSTA is very sensitive to the distance of a ¼ wavelength. For a larger fraction of the wavelength the dune face gets steeper. For a smaller fraction, also an irregular shape of the dune face is computed.
- The significant run-up in DUROSTA has limited influence on the erosion volumes.
- The method of extrapolation of transport over the dry profile gives unrealistic results regarding the location of the dune foot for simulations with higher wave periods. In reality the dune foot moves up to above the water level. Since the point of extrapolation forces the dune foot to be located near the water line in DUROSTA, this is not possible in DUROSTA simulations.
- The influence of the numerical smoothing factor on DUROSTA simulations is negligible.
- The influence of the slope factors (K_{sl} and K_{sw}) on DUROSTA simulations is very large. In the DUROSTA simulations used in this research, approximately 60 percent of the dune erosion is initiated by these two parameters.

- In DUROSTA the grid size mainly influences the shape of the upper part of the dune face. In case of a small grid size the predicted dune face gets steeper, which results in less dune erosion.

Sensitivity of the wave period effect

- In DUROSTA the net amount of dune erosion increases fast with an increasing wave period and water level. This relative effect on the erosion volumes is approximately the same for a range of wave periods between 6 and 24 seconds. The relative wave period effect is thus not affected by water level variations.
- In DUROSTA the wave height is a very important factor in predicting dune erosion. The wave period effect is highly influenced by the wave height, since the wave period effect increases significantly for larger wave heights.
- DUROSTA is very sensitive to the breaker index.
- The influence of the wave period is very small for low breaker indices (e.g. 0.6 and 0.7). For a larger breaker index the amount of erosion increases more quickly with an increasing wave period.
- Applying the breaker index according the Battjes and Stive (1985) in DUROSTA simulations, results in an inverse wave period effect for prototype wave periods larger than 11 seconds. In this case erosion volumes decrease with an increasing wave period, which is in contrast with the measurements.
- Application of the breaker index according to Ruessink *et al.*(2003) in DUROSTA simulations results in a significant underestimation of the amount of erosion for a range of wave periods between 6 and 24 seconds.
- In DUROSTA the net amount of dune erosion increases with a decreasing grain size. The wave period effect gets larger for a smaller grain size.
- When measured profiles from the physical model tests are used as initial profile in DUROSTA simulations, the influence on the end profile is very small.
- Applying the initial profile of test T08 shows that DUROSTA is also able to simulate a begin profile with an additional narrow dune. During the experiments the erosion process is however faster. This was also observed in the test T06 and T05.

6 Simulations on prototype scale

In the previous chapters DUROSTA simulations were only performed on model scale. In this chapter the performance of DUROSTA on prototype scale is studied. At first simulations are executed for the reference profile for the Dutch coast. This reference profile is considered to be a characteristic dune profile for the Dutch coast and is described in Paragraph 3.1.2. In the physical model tests the reference profile was scaled to fit the Delta flume. Comparing simulations of the reference profile on model scale and prototype scale may indicate whether scale effects play a role in simulating dune erosion with DUROSTA.
In Paragraph 6.2 the influence of 14 measured dune profiles along the Dutch coast is examined. It is studied whether the wave period effect calculated by DUROSTA for these real dune profiles agrees with the wave period effect as it was computed for the reference profile.
For both approaches a comparison is made between the DUROSTA results and the predictions of the existing empirical model DUROS (Vellinga, 1986) which is the basis in the safety assessment method used for the Dutch dune coast. Recently an extension of existing empirical model was proposed by Van Gent *et al*. (2007), in which the influence of the wave period is taken into account. The prediction of dune erosion with this adapted model is compared to the DUROSTA results as well.

6.1 Reference profile for the Dutch coast

For the physical model tests a coastal profile was constructed in the Delta flume, which was based on a reference profile that is considered to be characteristic for the Dutch coast. During the experiments a depth scale factor of n_d = 6 was applied. In addition a profile steepness factor of S_0 = 2 was used in order to make the profile fit the flume, see Paragraph 3.1.2.
To study the performance of DUROSTA on prototype scale, the initial profile constructed in the physical model tests is scaled up to prototype, which would in theory be equal to the reference profile for the Dutch coast. Some differences do however exist between the up-scaled reference profile from the physical model tests and the real reference profile (Appendix F.1). The dune profile applied in the physical model tests was for example cut off at 60 meters from the wave board, whereas the real reference profile has a continuous slope of 1:180 (seaward from NAP -3 m). Differences in the slope occur due to the additional steepness factor and inaccuracies in the constructed profile are possible. Besides simulations with the up-scaled reference profile additional DUROSTA simulations are therefore performed with the real reference profile. The (hydraulic) conditions during the simulations are given in Table 6.1. It should be noted that the sediment diameter is not scaled following the described scale relations. All simulations are carried out for a storm duration of 5.0 hours in prototype, since this condition is also used in the safety assessment of the Dutch coast.

Table 6.1 Conditions for simulations on model scale and prototype scale

	Model scale	Prototype scale
Water level	Flume bottom +4.50m	NAP +5.0m
Significant wave height	1.50 m	9.0 m
Peak wave period	4.90 s	12.0 s
Peak wave period	7.35 s	18.0 s
D_{50}	200 µm	225µm

The results of the simulations on model scale, prototype scale (up scaled from physical model tests) and for the real reference profile are shown in Appendix F.2. The corresponding erosion volumes are shown in Table 6.2.

Table 6.2 Computed erosion volumes [m^2/m] by DUROSTA after 5 hours

Erosion volume [m^2/m]	Model scale	Reference profile (upscaled from physical model tests)	Reference profile
Measurements (T_p=12.0 s)	5.9	(322)	-
Measurements (T_p=18.0 s)	7.4	(404)	-
DUROSTA. (T_p=12.0 s)	4.8	270	202
DUROSTA (T_p=18.0 s)	6.5	379	278

From the erosion volumes can be concluded that there is indeed a difference between the erosion in the scaled physical model tests and the real reference profile. However, the wave period effect in DUROSTA is approximately 38-40 percent for the simulations on prototype. On model scale the wave period effect was 35 percent, it seems therefore that scale effects only have a small influence in the DUROSTA simulations regarding the wave period effect.

The safety assessment which is presently applied for the Dutch dune coast is based on the so-called DUROS model. In the DUROS model the under water bed profile is calculated for normative hydraulic conditions with a parabolic erosion profile. The significant wave height at deep water, the water level and a characteristic diameter of the dune sand (related to fall velocity) are parameters used to calculate the shape of the parabolic erosion profile according to (Vellinga, 1986):

$$\frac{7.6}{H_{0s}} \cdot y = 0.4714 \left[\left(\frac{7.6}{H_{0s}} \right)^{1.28} \left(\frac{w}{0.0268} \right)^{0.56} \cdot x + 18 \right]^{0.5} - 2.0 \qquad (6.1)$$

The dune foot is defined at storm surge level and forms the origin of the erosion profile. Landward from this point the slope is fixed at 1:1. The erosion profile is applied between the origin and an offshore transition point. This location of this transition point is described by:

$$x_R = 250 \cdot \left(\frac{H_{0s}}{7.6} \right)^{1.28} \left(\frac{0.0268}{w} \right)^{0.56} \qquad (6.2)$$

Seaward from this transition point the slope is fixed at 1:12.5.

Finally the location of the erosion profile is obtained by horizontally moving the shape of the erosion profile until the total erosion volume is equal to the accretion volume, see Figure 6.1.

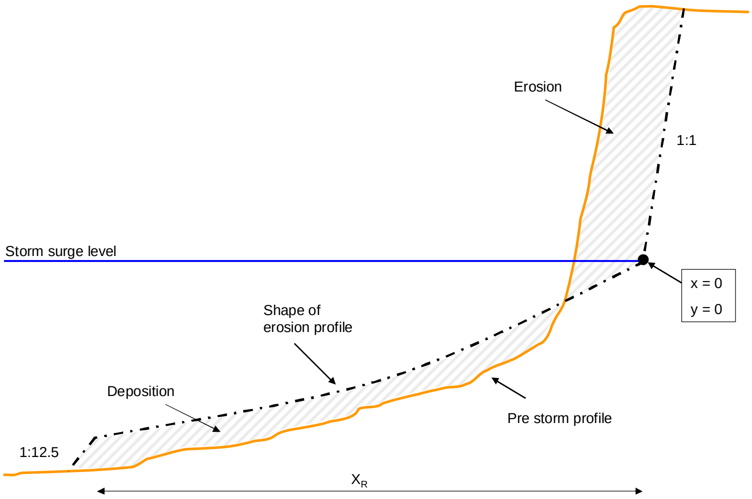


Figure 6.1 Principle of the DUROS model

Recently an extended version of the empirical DUROS model is proposed by Van Gent *et al*. (2007), which also takes the effect of the wave period on dune erosion into account. The adapted method is almost similar to the DUROS model, since the shape of the dune erosion profile is modified only by adding an extra term to include the wave period:

$$\frac{7.6}{H_{0s}} \cdot y = 0.4714\left[\left(\frac{7.6}{H_{0s}}\right)^{1.28}\left(\frac{12}{T_p}\right)^{0.45}\left(\frac{w}{0.0268}\right)^{0.56} \cdot x + 18\right]^{0.5} - 2.0 \qquad (6.3)$$

In this study the adapted method is called the DUROS+ model. It is stressed that a wave period of 12 seconds in the DUROS+ model gives the same results as the DUROS model. The computed erosion profiles according to these two empirical methods are also shown in Appendix F.2. The corresponding erosion volumes are given in Table 6.3.

Table 6.3 Computed erosion volumes [m²/m] by DUROSTA and the DUROS+ model for wave periods of 12 seconds and 18 seconds

Erosion volume [m²/m]	Model scale	Reference profile (upscaled from physical model tests)	Reference profile
DUROSTA (T_p=12.0 s)	4.6	270	202
DUROSTA (T_p=18.0 s)	6.4	379	278
DUROS / DUROS+ (T_p=12.0 s)	12.1	506	385
DUROS+ (T_p=18.0 s)	14.3	612	469

From the erosion volumes can be concluded that the DUROS+ model overestimate the DUROSTA results significantly for wave periods of 12 and 18 seconds. For simulations on model scale this overestimation is a factor 2.6 and 2.2 for respectively a wave period of 12 and 18 seconds. For simulations on prototype scale this respectively a factor 1.9 and 1.7. It is however stressed that the DUROS(+) model uses a robust approach. The general idea of a process based model like DUROSTA is that by including physical processes a more accurate computation is possible and less safety margins are required within the model. The large difference in results for model scale and prototype scale is remarkable and may be explained by the fact that scale relations are included different in DUROSTA than in the emperical methods. Further research on this aspect is however required.

It is stressed that the DUROS+ model with T_p=12s (and in the future the DUROS+ model with T_p=18s) is only used as the basis of the actual safety assessment method for the Dutch dune coast (TAW, 1984). This safety assessment method is developed using a probabilistic approach. Applying the probabilistic method may result in different conclusions.

6.2 Real dune profiles along the Dutch coast

At last several DUROSTA simulations are performed on 14 real dune profiles, which have been measured along the Dutch coast within the so-called JARKUS program. These profiles include dune profile along the central Dutch coast (Noord-Hollandse kust) and dune profiles of the wadden islands. Simulations have been carried out for peak wave periods of 12 and 18 seconds to examine whether the wave period effect predicted for the reference profile (which is considered characteristic for the Dutch dune coast) agrees with the wave period effect which is computed for real dune profiles. The same conditions are used as is the previous paragraph (see Table 6.1). The resulting erosion profiles are shown in Appendix F.3. Corresponding erosion volumes are shown in Table 6.4.

Table 6.4 Erosion volumes and wave period effect computed by DUROSTA and DUROS(+) after 5 hours for real dune profiles

Locations	Erosion volume [m2/m] DUROSTA T_p=12s /T_p=18s	Wave period effect in DUROSTA [%]	Erosion volume [m2/m] DUROS+ T_p=12s /T_p=18s	Wave period effect in DUROS [%]
Den Helder	63/143	127	198/255	29
Botgat	118/167	42	287/375	31
Zwanenwater	166/212	28	369/466	26
Tweede korftwater	165/220	33	353/428	21
Egmond	105/149	42	249/342	37
Zandvoort	76/110	45	182/276	52
Noordwijk	84/119	42	160/213	33
Scheveningen	95/147	55	208/287	38
Hoek van Holland	54/87	61	63/109	73
Texel	112/154	38	275/357	30
Vlieland	112/151	32	233/302	30
Terschelling	17/33	94	-	-
Ameland	57/75	32	81/157	94
Schiermonnikoog	25/17	-32	-/3	-

From the table is concluded that a significant variability of the computed wave period effect is present between the different locations. Averaging the results for all 14 locations gives a mean wave period effect of 46 percent for DUROSTA computations and 41 percent for DUROS+ computations. The 46 percent is slightly larger compared to the 40 percent that was found for the calculations with the reference profile. Also for these real dune profiles it is observed that the probabilistic prediction methods again significantly overestimate the DUROSTA results.

6.3 Conclusions

In this paragraph the main conclusions from this chapter are summarised.

- For simulations with the reference profile on prototype scale, the wave period effect computed by DUROSTA is approximately 40 percent. This percentage was 35 for simulations on model scale. It is therefore concluded that scale effects have a small influence in the DUROSTA simulations regarding the wave period effect.
- The DUROS+ model overestimates the computed erosion volumes by DUROSTA significantly for wave periods of 12 and 18 seconds. For simulations on model scale this overestimation is a factor 2.6 and 2.2 for respectively a wave period of 12 and 18 seconds. For simulations on prototype scale this respectively a factor 1.9 and 1.7.
- There is a large difference between the overestimation of the DUROSTA results by DUROS+ on model scale and prototype scale. This may be explained by the fact that scale relations are included different in DUROSTA than in the empirical models.
- DUROSTA simulates a significant variability of the wave period effect for different locations along the Dutch coast. The mean wave period effect is 46 percent for measured dune profile along the Dutch coast, which is slightly larger than the 40 percent that was found for the simulations with the reference profile.

7 Conclusions and Recommendations

In this chapter the main conclusions of this study are summarised. Subsequently also some recommendations for further research are proposed.

7.1 Conclusions

The objective of this study is to validate the DUROSTA model taking into account the influence of the wave period. As a first step in the validation of the model, the performance of the sub models in DUROSTA is studied to obtain better insight in the physical processes within the model. An important part of this analysis examines the performance of the sub models regarding the influence of the wave period. Simulations were carried out with peak wave periods of 12 and 18 seconds and compared to results from large scale physical model tests. From the analysis the following conclusions are drawn:

- For initial computations, the wave propagation model (ENDEC, Battjes and Janssen, (1978)), functions well for default settings (i.e. γ = 0.85) in the near dune area. The wave height measurements are slightly overestimated in this area for both wave periods. In the middle of the profile the agreement is less good, since DUROSTA overestimates the wave height in this area especially for a larger wave period.
- Both the measurements from the physical model tests and the DUROSTA computations show a larger wave height over the entire profile in case of a larger wave period.
- The undertow velocities are in general underestimated by DUROSTA at deeper water. Especially for a smaller wave period DUROSTA underestimates the measurements significantly up to a factor 2.
- Computed velocities by DUROSTA are slightly higher for a larger wave period. It is therefore concluded that a larger wave period also results in larger undertow velocities in DUROSTA simulations. This tendency is not observed this clearly in the physical model tests.
- DUROSTA underestimates the sediment concentrations significantly, especially close to the dune. The sediment concentrations computed by DUROSTA are concentrated in a very small range, whereas the measurements show a much larger spreading of concentrations, especially in the direction of the dune.
- Computed sediment concentrations are in general higher for the larger wave period. This trend was also observed in the measurements. During the physical model tests, concentrations increase with a factor 2 in the near dune area with an increasing wave period.
- For a low wave period, the overall magnitude of the sediment transport is computed well compared to the sediment transport calculated from the measured bed level change. Also trends in time and space are simulated well in this case. For a higher wave period the agreement is less good. The maximum transport is not located at the dune foot but further seaward, indicating erosion in front of the dune foot for initial calculations.
- In both the large scale experiments and in the DUROSTA simulations the wave period effect presents itself mainly in higher sediment concentrations, rather than in higher undertow velocities.

To be able to compare measurements from the physical scale tests directly with the results of the DUROSTA sub models, only initial computations were carried out. It was therefore not possible to gain insight in the profile development in time. To gain insight in the integral performance of DUROSTA, full test simulations are carried for wave periods of 12 and 18 seconds and compared to results from large scale physical model tests. From this analysis the following conclusions are drawn:

- DUROSTA simulates the profile development in general well for a peak wave period of 12 and 18 seconds. The retreat of the dune crest is underestimated for both wave periods.
- For a wave period of 12 seconds DUROSTA consistently underestimates the erosion volumes. For a wave period of 18 seconds, the erosion volumes are predicted rather well.
- In both the large scale physical model tests and the DUROSTA model a wave period effect was observed, i.e. an increasing amount of dune erosion in case of a larger wave period. After 2.04 hours (5.0 hours in prototype) the relative increase in erosion volume is 25 percent in the physical model tests and 35 percent in DUROSTA computations. After six hours (model scale) the wave period effect has decreased to 15 percent in the measurements. For DUROSTA computations the effect has increased to 43 percent.

Comparison of the performance of the DUROSTA sub models and the integral performance of DUROSTA showed that, besides the physical processes represented by the DUROSTA sub models, other processes has to be included in DUROSTA which have a large influence on predicting dune erosion. In this respect several components and factors are studied in more detail, i.e. the method of modelling sediment transport over the dry profile, numerical smoothing, slope correction factor, grid size and the location of the dune foot. Based on this analysis the following conclusions are drawn:

<u>Modelling of sediment transport over the dry profile</u>

- The influence of different extrapolation methods, i.e. no extrapolation, horizontal extrapolation, vertical extrapolation and the default DUROSTA extrapolation, on the profile development in DUROSTA is relatively small. From this is concluded that the significant run-up is important in modelling the shape of the retreating dune face.
- According to the literature (Steetzel, 1993) the point at a ¼ wavelength seaward of the waterline is used as the transition point between the wet and dry profile. However, in the DUROSTA code the last wet computing point before the water line is used as the start of extrapolation of sediment transport over the dry profile. The ¼ wavelength is used in the calculation of the reduction factor and the determination of the relative wave run-up.
- DUROSTA is very sensitive to the distance of a ¼ wavelength. For a larger fraction of the wavelength the dune face gets steeper. For a smaller fraction, an irregular shape of the dune face is computed.
- The significant run-up in DUROSTA has limited influence on the amount of dune erosion. This is remarkable since the run-up was assumed to be the governing physical parameter in the calculation of the reduction factor.
- In DUROSTA the method of extrapolation of transport over the dry profile forces the dune foot to be located near the water line. However during the physical model tests the dune foot moves up to above the water level, especially for a peak wave period of 18

seconds. DUROSTA simulations give therefore unrealistic results regarding the location of the dune foot for simulations with a wave period of 18 seconds.

Numerical smoothing

- The influence of the numerical smoothing factor on the DUROSTA simulations in this study is negligible.

Bed slope effects

- It is noted that the swash factor K_{sw} is defined different in the DUROSTA code than in the literature (Steetzel, 1993). Here it was described as an additional numerical smoothing factor, whereas in the DUROSTA code K_{sw} is defined as an additional slope effect.
- The influence of bed slope effects on DUROSTA simulations in this study is very large. It was found that 60 percent of the dune erosion is initiated by bed slope effects.

Grid size

- In DUROSTA the grid size mainly influences the shape of the upper part of the dune face. In case of a small grid size the predicted dune face gets steeper and in less dune erosion is computed. For a larger grid size the effect is the other way around.

A sensitivity analysis is performed to get a better insight in the influence of the main physical parameters on the computations. The analysis focuses on the sensitivity of the different parameters in relation to the wave period. In this way it is studied how the wave period effect on dune erosion is influenced by certain other physical parameters, i.e. water level, wave height, breaker index and grain size. Additionally the influence of the initial profile is examined. From the sensitivity analysis the following conclusions are drawn:

Water level

- In DUROSTA the amount of dune erosion increases fast with an increasing wave period and water level. The relative wave period effect is not affected by water level variations.

Wave height

- In DUROSTA the wave height is a very important factor in predicting dune erosion. The wave period effect is highly influenced by the wave height, since the wave period effect increases significantly for larger wave heights.

Breaker index

- DUROSTA is very sensitive to the breaker index. This is also expected since the breaker index was one of the main calibrations parameters and directly determines the wave energy dissipation due to wave breaking and by that wave transformation over the profile.
- Applying the breaker index according the Battjes and Stive (1985) in DUROSTA simulations, results in an inverse wave period effect for prototype wave periods larger than 11 seconds. In this case erosion volumes decrease with an increasing wave period, which is in contrast with the measurements.
- Application of the breaker index according to Ruessink *et al.* (2003) in DUROSTA simulations results in a significant underestimation of the amount of erosion.

Grain size

- In DUROSTA the net amount of dune erosion increases with a decreasing grain size. The wave period effect gets larger for a smaller grain size.

Initial profile

- When measured erosion profiles from the physical model tests are applied as initial profile in DUROSTA simulations, the influence on the end profile (6 hours) is very small.

Simulations on prototype scale are carried out the study whether scale effects play a role in DUROSTA simulations. The hydraulic conditions used for these simulations are wave periods of 12 and 18 seconds and a wave height of 9 meter. Computed erosion profiles after 5 hours are compared to the DUROS+ model as well. From this analysis the following main conclusions are drawn:

- For simulations with the reference profile on prototype scale, the wave period effect computed by DUROSTA is approximately 40 percent. This percentage was 35 for simulations on model scale. It is therefore concluded that scale effects have a small influence in the DUROSTA simulations regarding the wave period effect.
- The DUROS+ model overestimates the computed erosion volumes by DUROSTA significantly for wave periods of 12 and 18 seconds. For simulations on model scale this overestimation is a factor 2.6 and 2.2 for respectively a wave period of 12 and 18 seconds. For simulations on prototype scale this respectively a factor 1.9 and 1.7.
- There is a large difference between the overestimation of the DUROSTA results by DUROS+ on model scale and prototype scale. This may be explained by the fact that scale relations are included different in DUROSTA than in the empirical models.
- DUROSTA simulates a significant variability of the wave period effect for different locations along the Dutch coast. The mean wave period effect is 46 percent for measured dune profile along the Dutch coast, which is slightly larger than the 40 percent that was found for the computations with the reference profile.

7.2 Recommendations

- From the data analysis was concluded that long waves become more important towards the dune. It is therefore recommended to include long waves in a new dune erosion prediction method. It should be studied in what way long waves contribute to dune erosion during a storm surge and how long waves can be implemented in a dune erosion model.
- It is recommended to find a method which enables more accurate velocity measurements in the inner surf and swash zone.
- The ENDEC model is not suitable for a proper wave decay computation over the entire profile. It is recommended to examine how simulating the wave height decay over the entire profile can be improved.
- The flow velocity model in DUROSTA is based on the assumption of an undertow. This assumption is most probable not valid in the inner swash zone. It is therefore recommended to study in more detail how modelling of the swash zone flows can be improved.

- Near dune sediment concentrations are significantly underestimated by DUROSTA. It is therefore recommended to examine how modelling of sediment concentrations close the dune can be improved.
- DUROSTA simulates the location of the dune foot especially for large wave periods too low compared to measurements from the physical model tests. This is explained by the method of extrapolation of transport over the dry profile. It is therefore recommended to develop another method for computing sediment transport over the dry profile.

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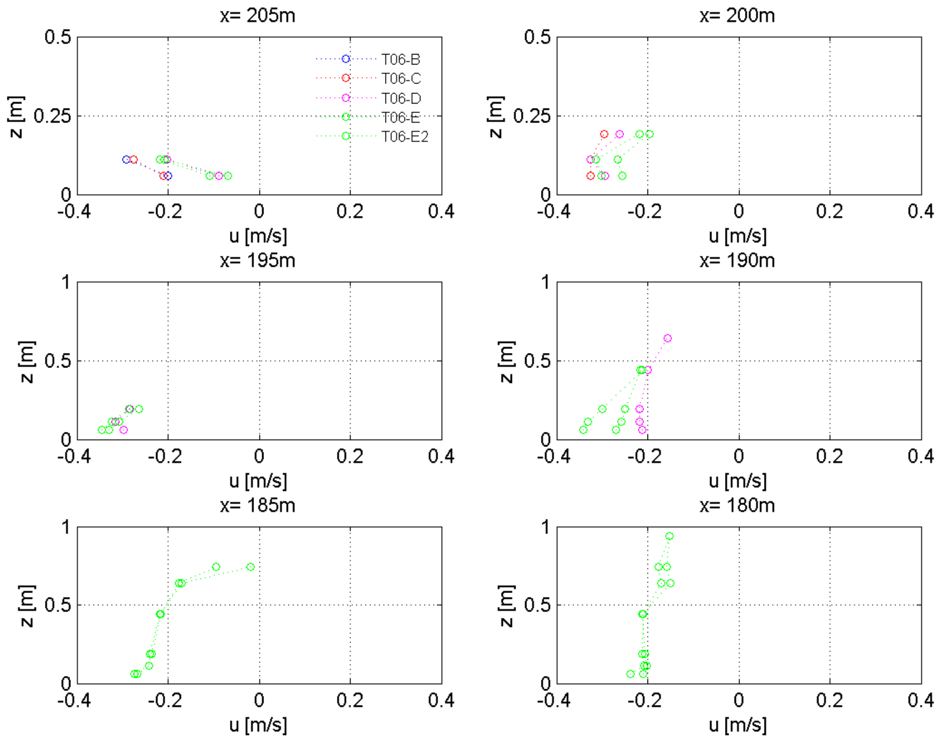
A Measurement programme shallow water frame

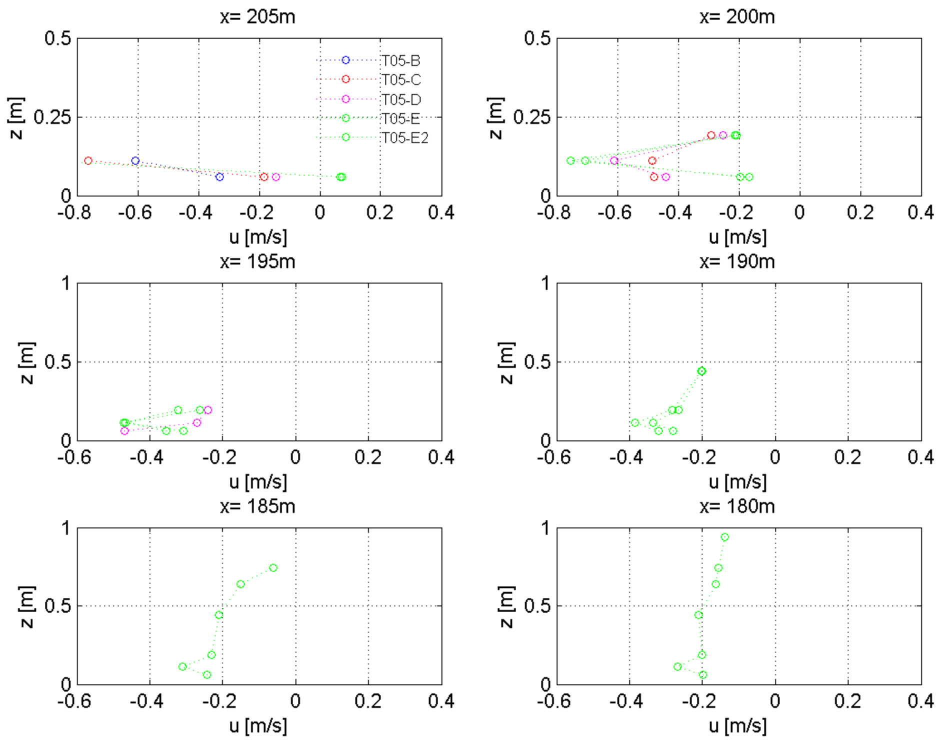
Table A-1 Measurement programme shallow water frame: cross-shore position shallow water frame (m) as function of test interval and measurement number within test interval

Test	Measurement Interval														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
T01C	150														
T01D	130														
T01E	170	130	100	160											
T03C	130														
T03D	150	150	150												
T03E	100	115	70												
T05A	170														
T05B	205														
T05C	205	200													
T05D	205	200	195												
T05E	205	200	195	190	185	180	205	200	195	190					
T05F	170	160	150	140											
T06A	170														
T06B	205														
T06C	205	200	170												
T06D	205	200	195	190											
T06E	205	200	195	190	185	180	205	200	195	190	185	180	175	170	
T06F	205	200													
T06G	205	200	195	190	185	205	200	195							
T06H	182	184	186	188	189	190	191	192	194						
T06I	170														
T08A	170														
T08B	205														
T08C	205	190													
T08D	190	185	205	190											
T08E	210	205	200	195	190	185	180	205	200	190	98	80	70	60	
DP01A	190														
DP01B	190														
DP01C	190	185	180												
DP01D	190	185	180	190											
DP01E	180	205	200	195	190	185	180	205	200	195	190	185	180	205	200
DP01F	190														
DP02C	150														
DP02D	130														
DP02E	195	200	205	210											

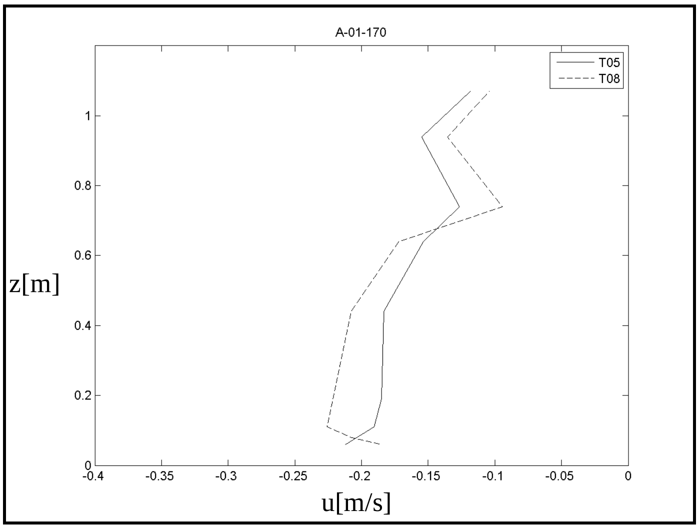
B Data Analysis

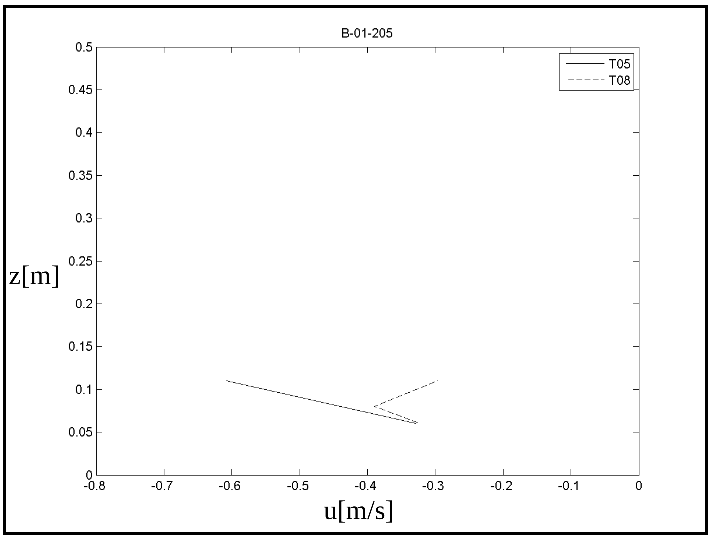
B.1 Velocity verticals

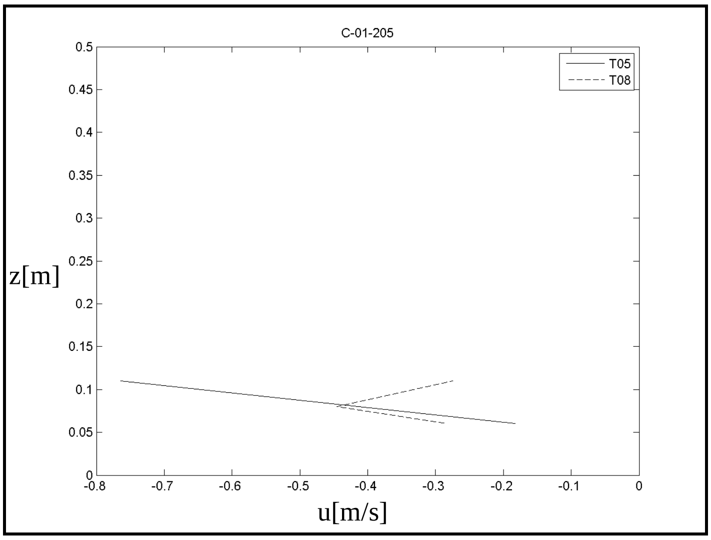




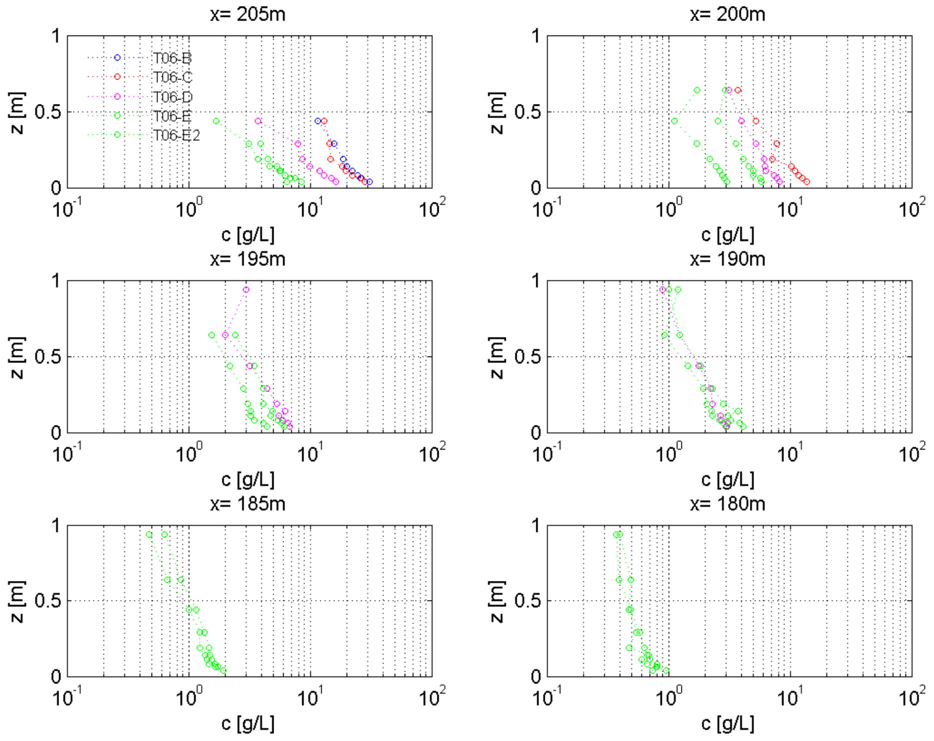
B.1.1 Comparison of velocity verticals test T05-T08

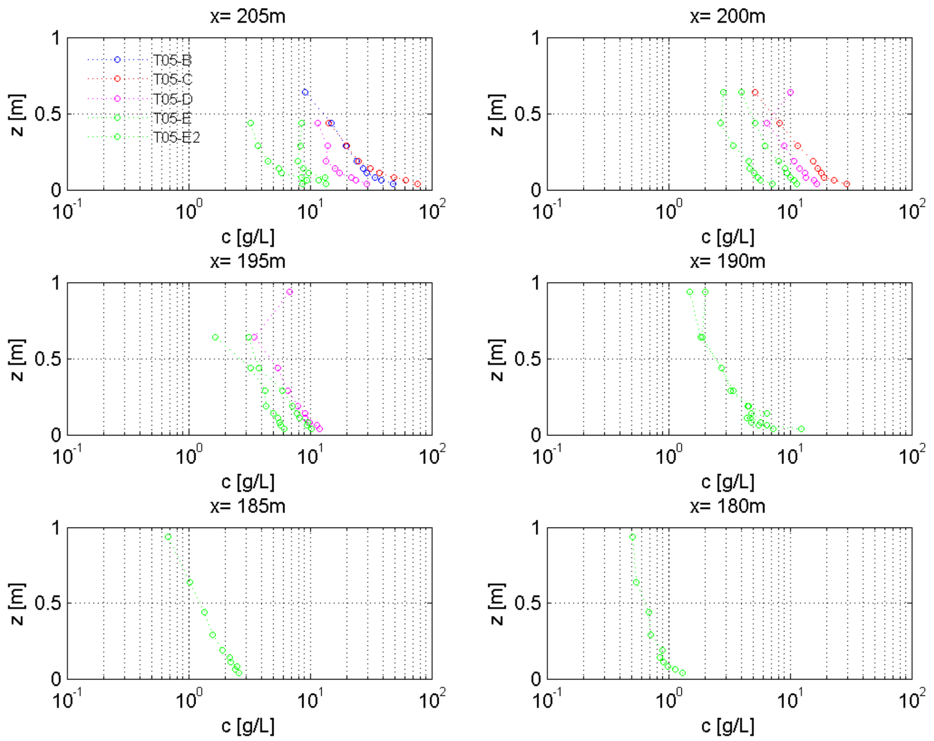




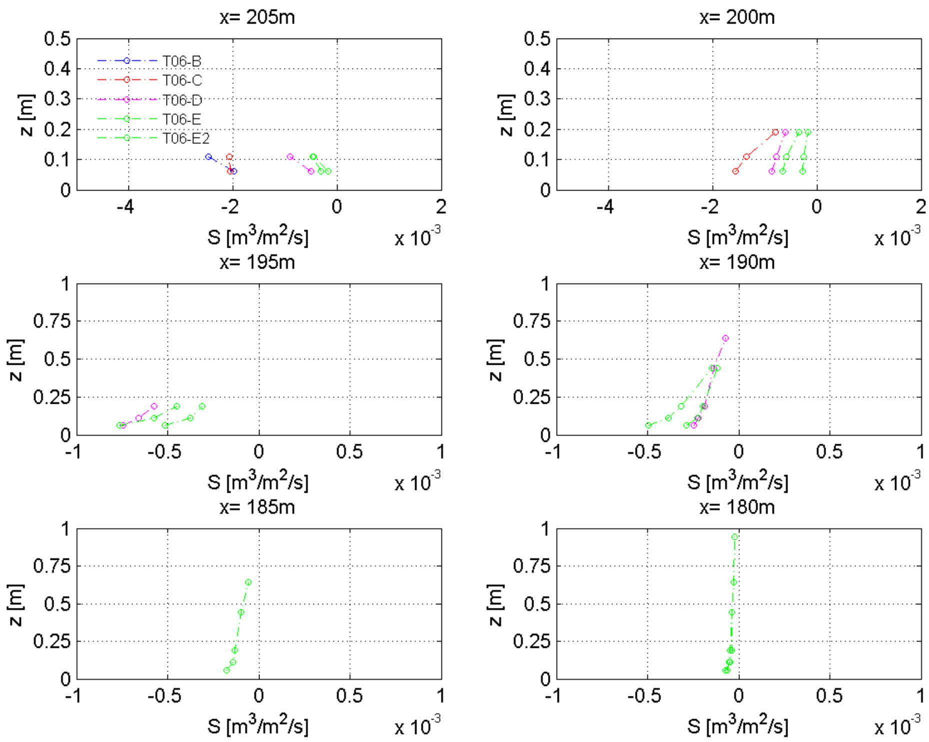


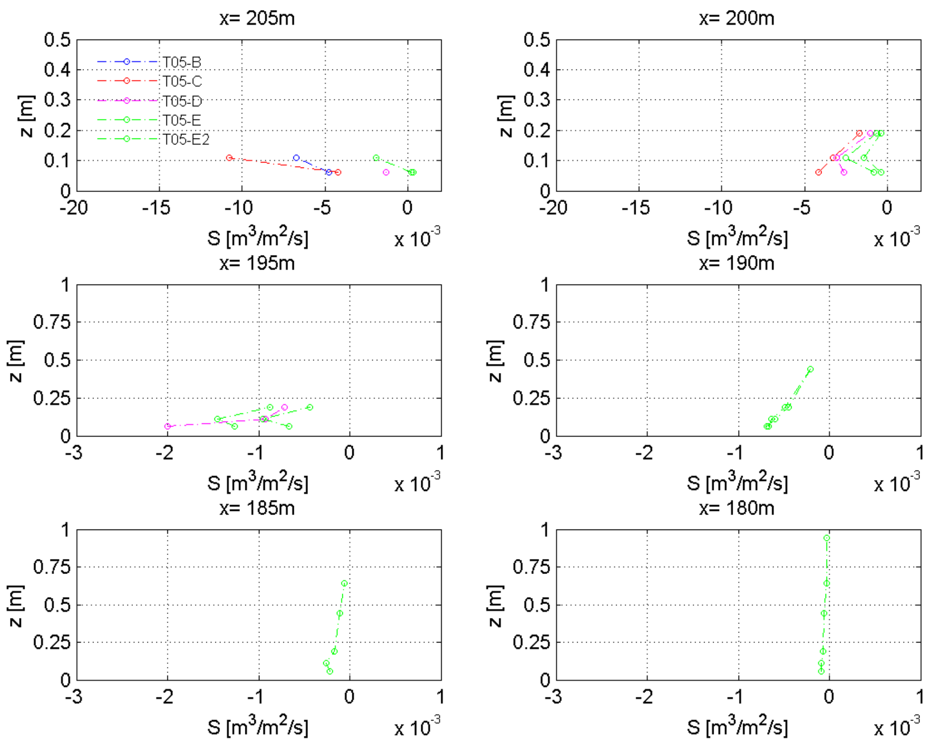
B.2 Sediment concentration verticals





B.3 Sediment transport verticals





C DUROSTA analysis

C.1 Input parameters DUROSTA

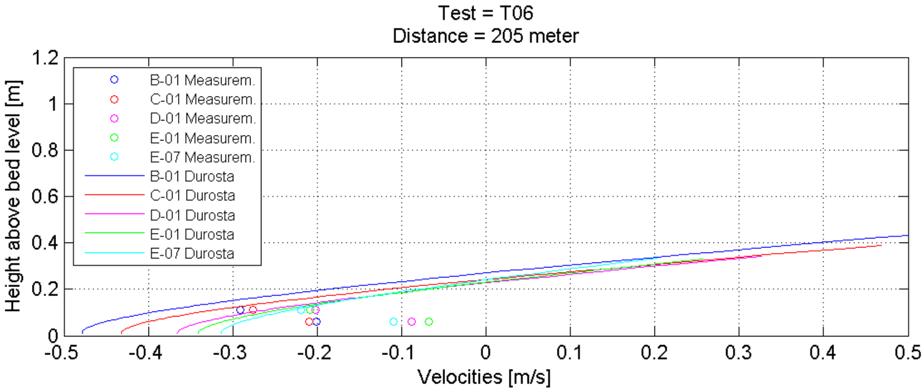
C.1.1 Default input parameters

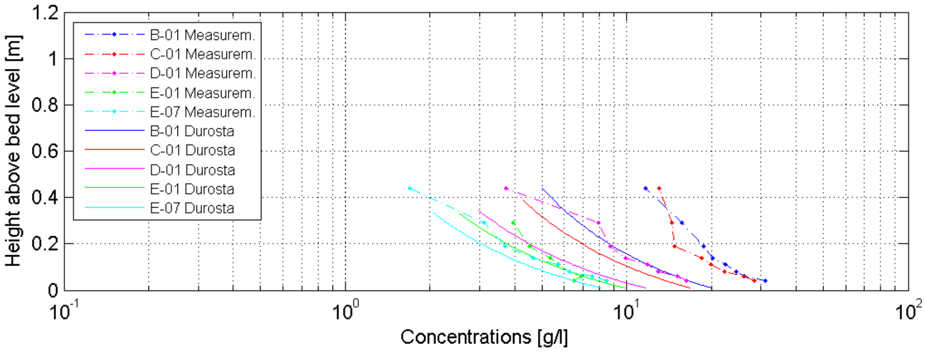
	Symbol	Description	Value	Unit
Wave	α	Factor in wave energy dissipation formulation	1	-
	fw	Roughness factor in energy dissipation formulation	0.01	-
	fzs	Factor in significant wave run-up (not defined in report)	1.0	-
	γ	Maximum breaker index	0.85	-
Concentration	α_D	Factor in F_D-formulation	1.2	-
	K_c	Coefficient in C_0 formulation	1.2*e-6	-
	α_k	Factor in penetration depth formulation	0.5	-
Mixing	K_ε	Coefficient in ε_0 formulation	21.9	-
	K_μ	Coefficient in $\varepsilon(z)$ formulation	8.5*e-3	-
Flux	K_r	Dimensionless coefficient of roller area and H_{rms}^2	0.9	-
	Kflux	factor for smoothing in upper profile (not defined in report)	1.0	-
Transport	K_{cor}	Transport correction factor	1.6	-
	K_{sl}	Coefficient in slope transport	4.0	-
	K_{sw}	Smoothing factor for swash	2.0	-
Bottom change	γ	Numerical smoothing factor in bed updating formulation	0.05	-
	Δt_{max}	maximum allowed time step	0.1	[h]

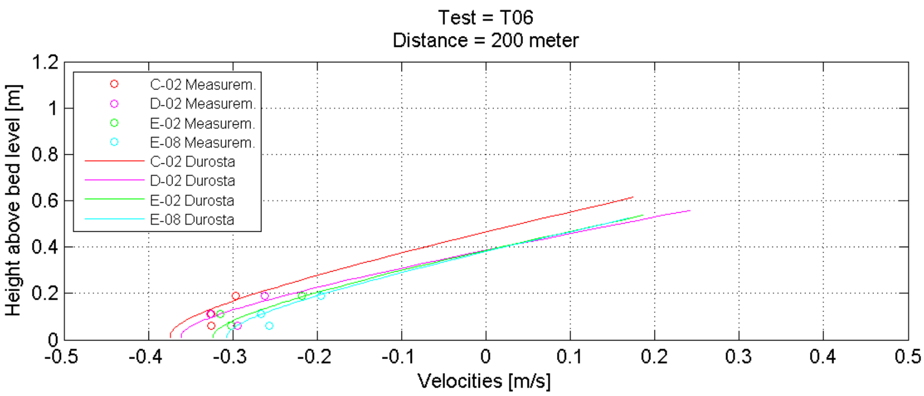
C.1.2 Adapted input parameters

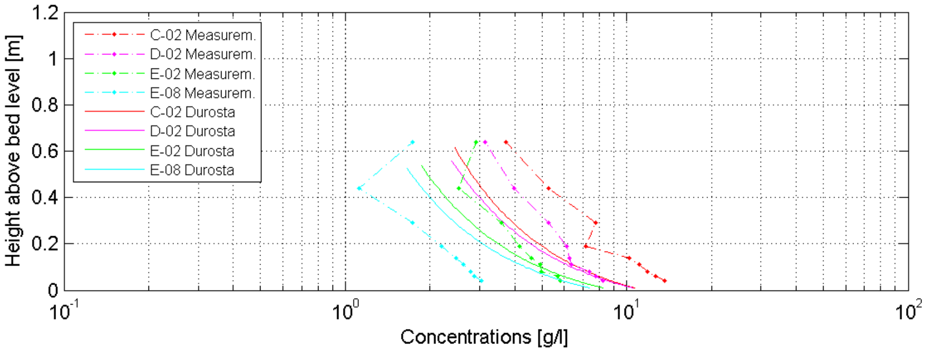
	Symbol	Description	Value	Unit
	Δz_{max}	maximum allowed depth change per time step	0.05	[m]
	D_{n50}	Sediment diameter	0.0002	[m]
	w_s	Fall velocity of sediment	0.022	[m/s]

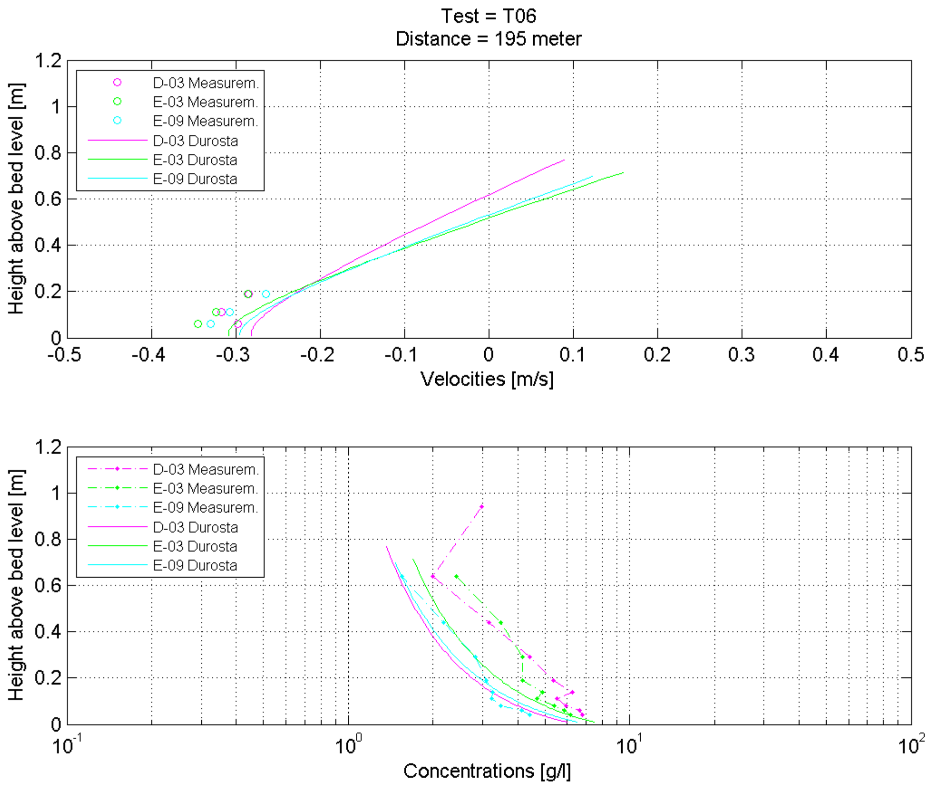
C.2 Velocity and concentration verticals T06







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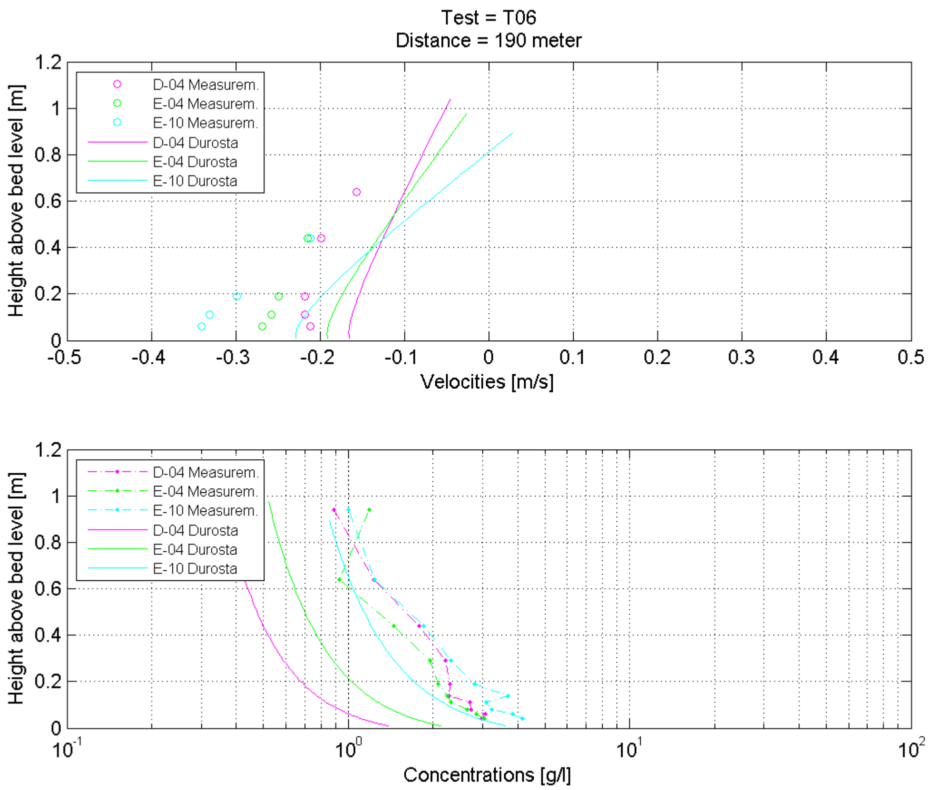
D-03 Measurem.
E-03 Measurem.
E-09 Measurem.
D-03 Durosta
E-03 Durosta
E-09 Durosta
Height above bed level [m]
Velocities [m/s]
Concentrations [g/l]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D-04 Durosta
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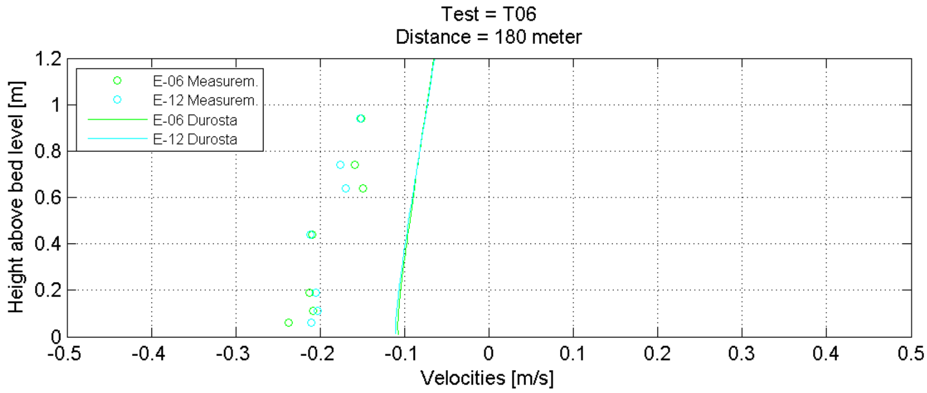
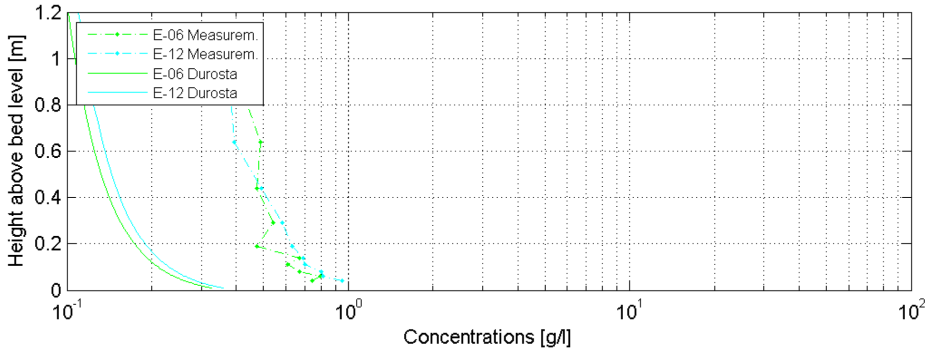
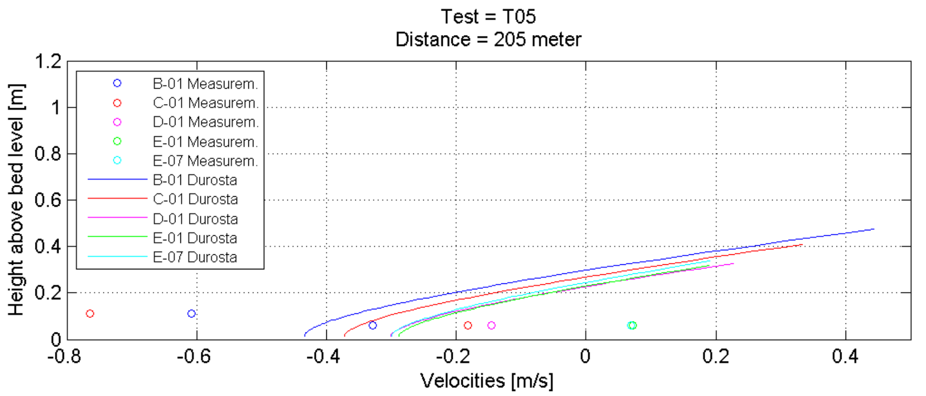
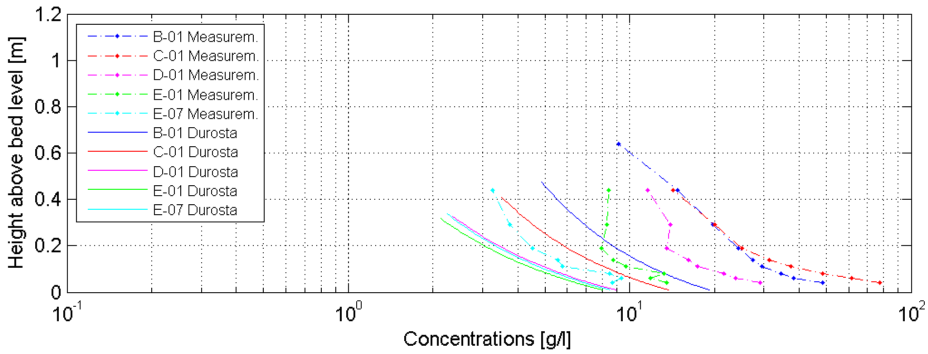
Height above bed level [m]
Velocities [m/s]
Concentrations [g/l]

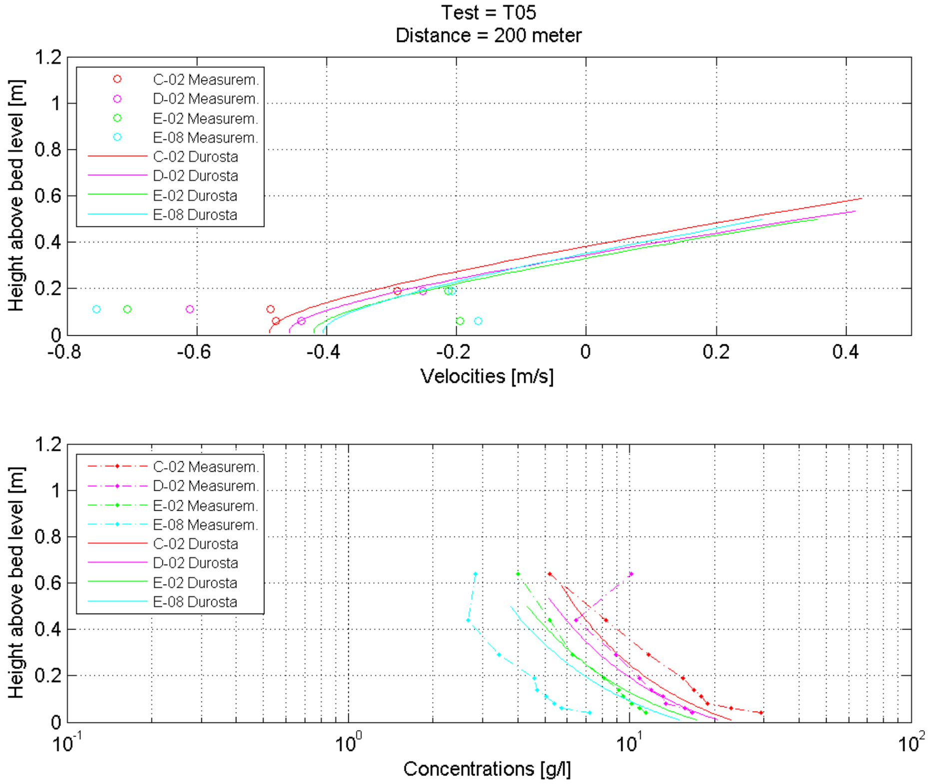


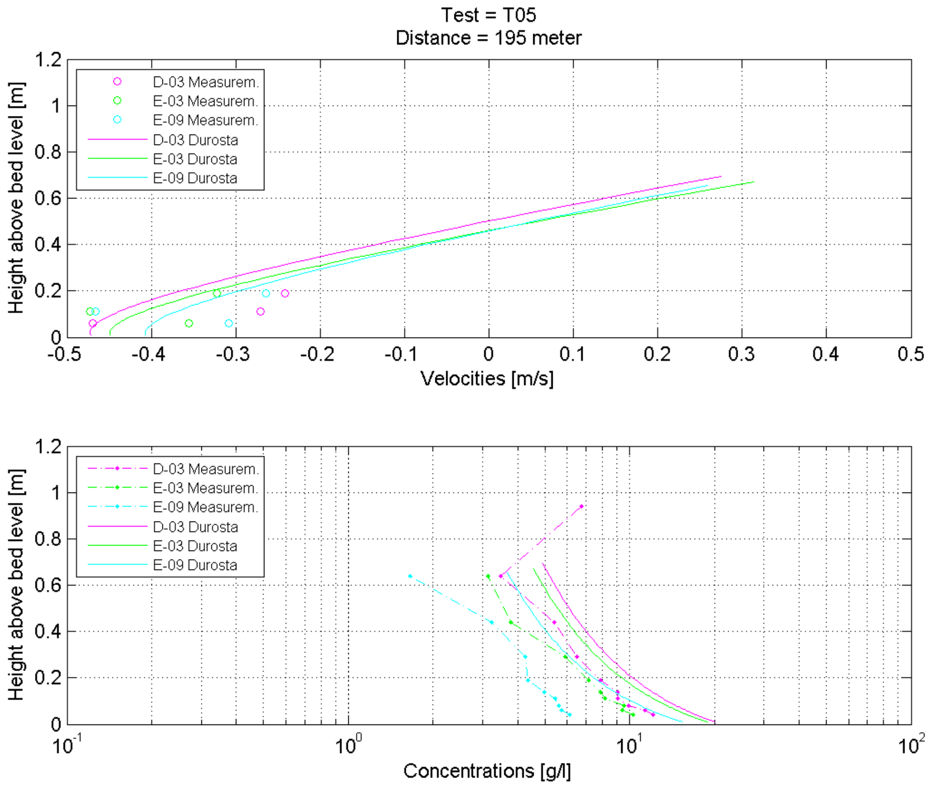


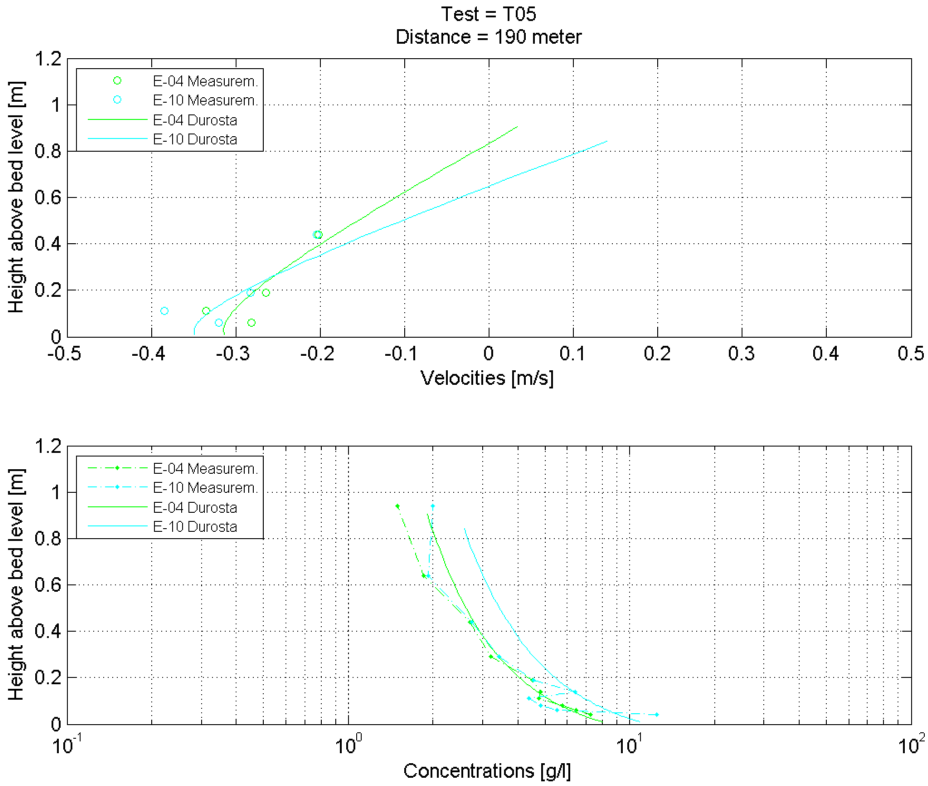
C.3 Velocity and concentration verticals test T05

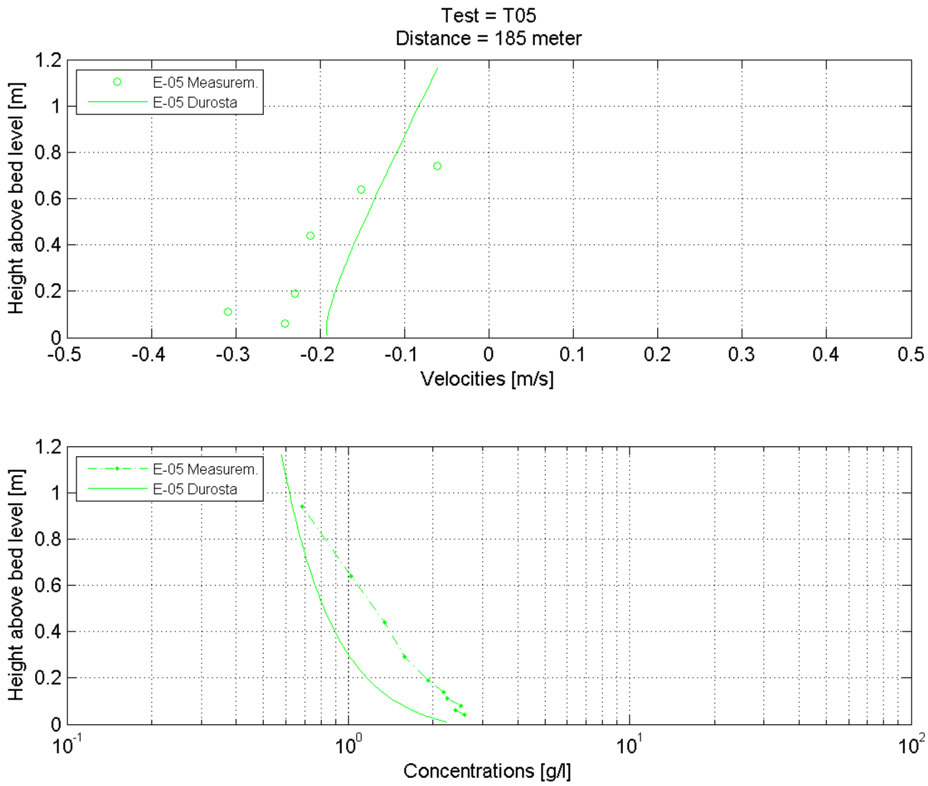


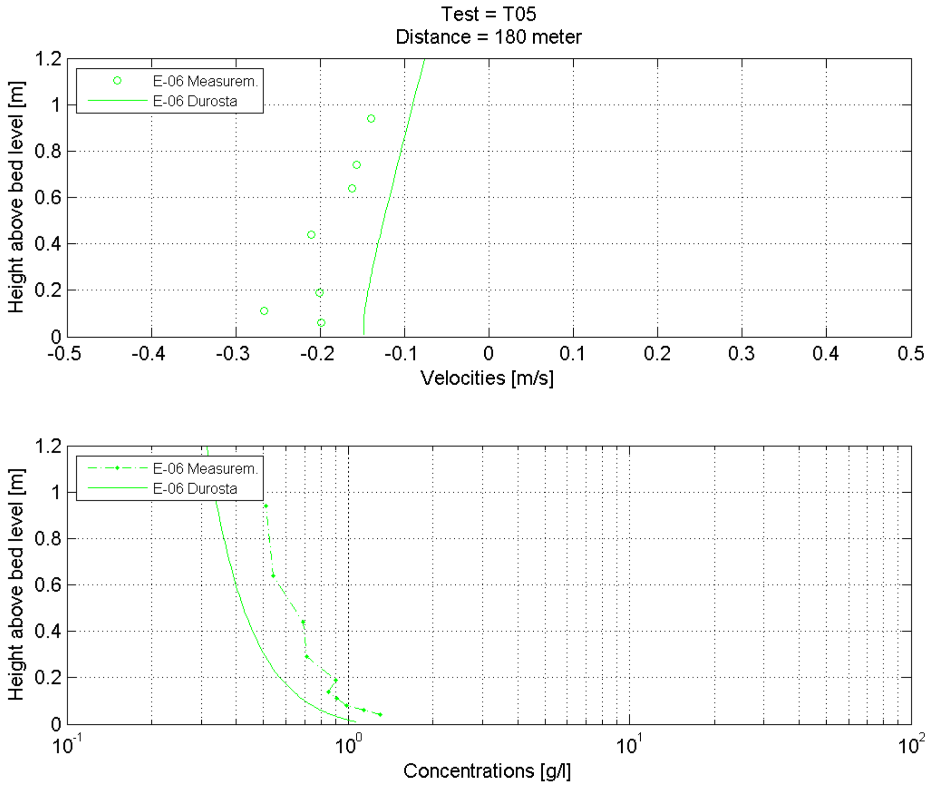



Test = T05
Distance = 200 meter
Height above bed level [m]
Velocities [m/s]
C-02 Measurem.
D-02 Measurem.
E-02 Measurem.
E-08 Measurem.
C-02 Durosta
D-02 Durosta
E-02 Durosta
E-08 Durosta
Height above bed level [m]
Concentrations [g/l]


Test = T05
Distance = 195 meter
Height above bed level [m]
Velocities [m/s]
D-03 Measurem.
E-03 Measurem.
E-09 Measurem.
D-03 Durosta
E-03 Durosta
E-09 Durosta
Height above bed level [m]
Concentrations [g/l]


Test = T05
Distance = 190 meter
E-04 Measurem.
E-10 Measurem.
E-04 Durosta
E-10 Durosta
Height above bed level [m]
Velocities [m/s]
Concentrations [g/l]


Test = T05
Distance = 185 meter
E-05 Measurem.
E-05 Durosta
Height above bed level [m]
Velocities [m/s]
Concentrations [g/l]



C.4 Additional research flow velocities

To be able to explain the underestimation of the measured velocities further from the dune, for both the measurements and DUROSTA the mass flux is calculated. In this way the influence of the assumed local trough level can be avoided. The mass flux in DUROSTA is computed according to Equation (2.18) and mass flux from measurements is calculated according to:

$$m = \frac{E}{c} = \frac{1/8 \rho g H_{rms}^2}{\sqrt{gd}}$$

were H_{rms} is the root-mean square wave height due to short waves only. The wave celerity c is assumed to be is this case (shallow water) approximately $\sqrt{gd}$, were d represents the mean water depth. Main differences between the two methods are that DUROSTA also takes a roller part into account and the fact that DUROSTA uses the dispersion relation to calculate the wave celerity. The results are shown in the figure below for test T06 (upper plot) and T05 (lower plot). It should be stressed that in the computation of mass flux from measurements only high frequency waves are taken into account.

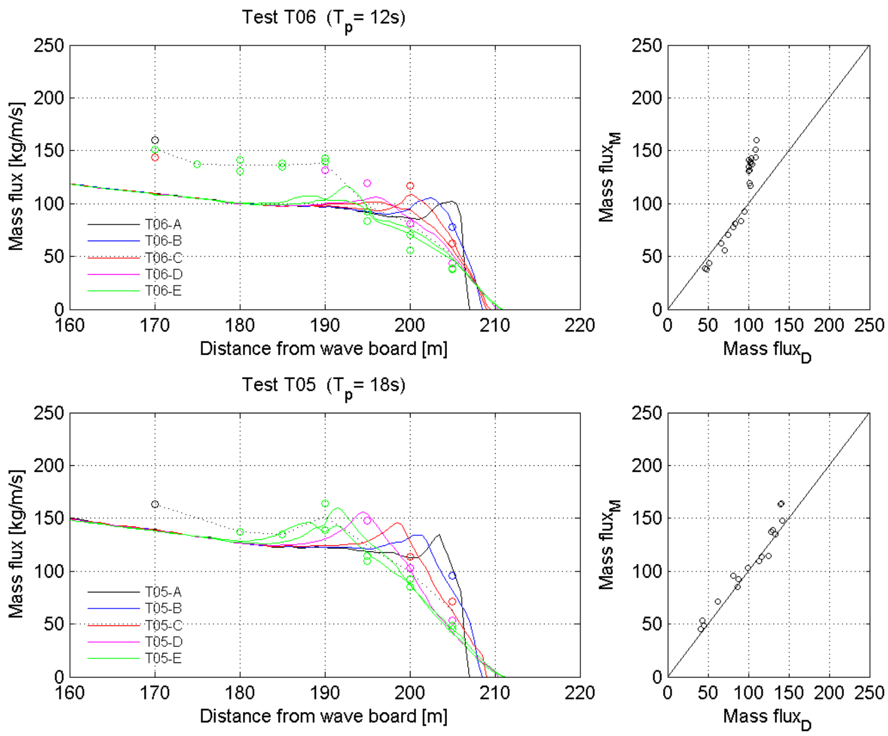


Figure C.1 Mass flux with only high frequency waves for test T06 and T05

In this figure the underestimation of DUROSTA for test T06 further from the dune is also observed. Differences are however reduced to a factor 1.5 instead of 2. From this can be concluded that differences must be caused by either differences in wave height or differences in wave celerity. Paragraph 4.2 showed that the wave height at these locations was simulated rather well; this is also shown in the correlation graph below. Small deviation however can be observed at larger distances for test T06.

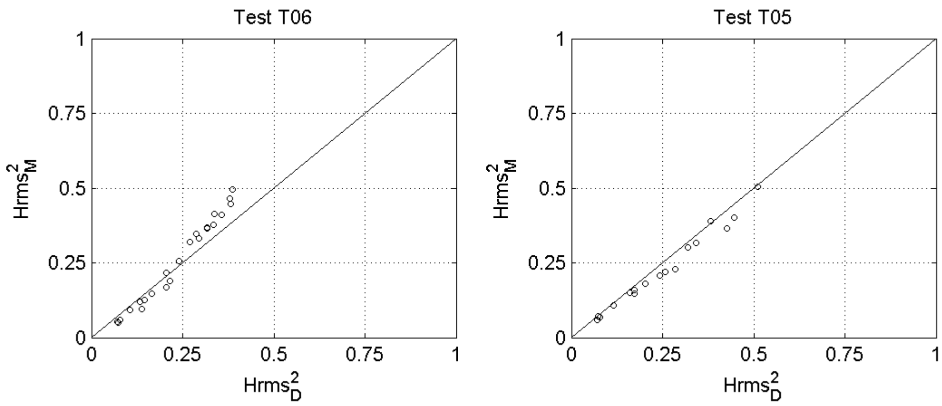


Figure C.2 Correlation between measured and computed root mean square wave height of only high frequency waves for test T06 and T05

Another possibility is that differences can be explained by differences in computed and measured wave celerity. The figure below shows the correlation of the wave celerity for both tests.

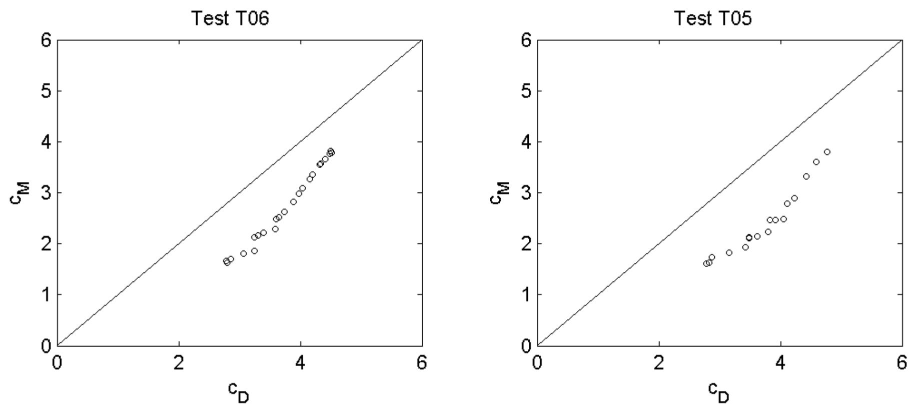


Figure C.3 Correlation between measured and computed wave celerity for test T06 and T05

From this graph can be concluded that DUROSTA systematically overestimates the wave celerity, which results in an in general lower computed mass flux. This consistent overestimation may be caused by the fact that DUROSTA assumes a constant deep water wave period. This does however not explain the consistently lower computed mass flux for test T06 at deeper water. In this respect mass flux of computations was also calculated by using computed wave energy but dividing this with the measured wave celerity ($\sqrt{gd}$). This is shown in the figure below:

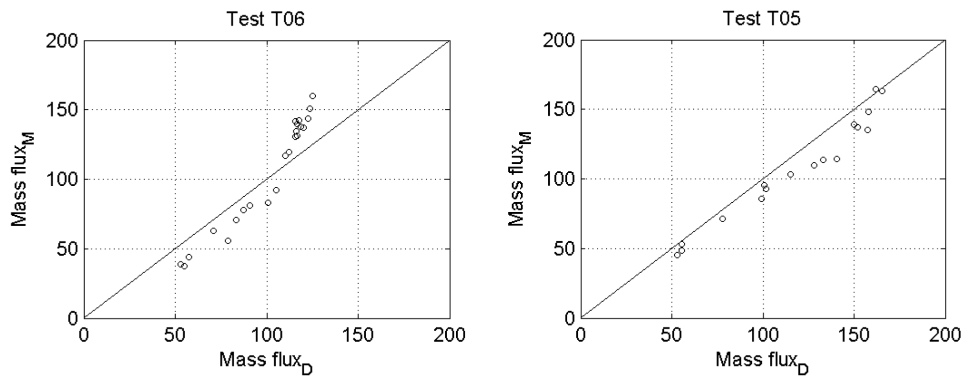


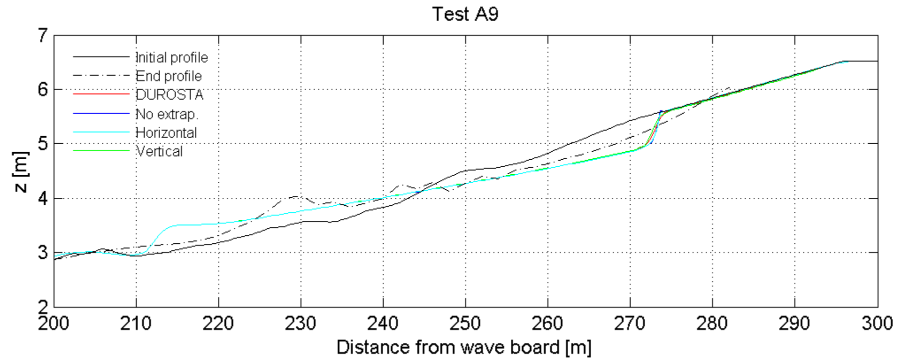
Figure C.3 Correlation between measured and computed mass flux for test T06 and T05

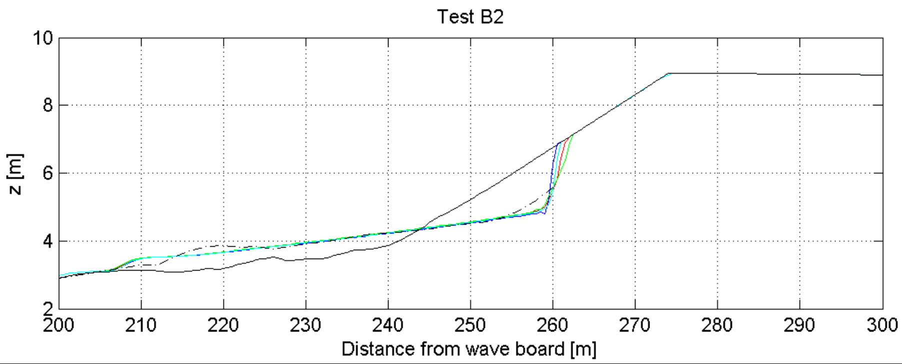
Theoretically these correlation graphs should look the same as the correlation graph of the wave height. Dividing by the wave celerity, although now equal for DUROSTA and measurements, makes the points however being ‘compressed’. This graph shows then again clearly that points at deeper water are underestimated by DUROSTA.

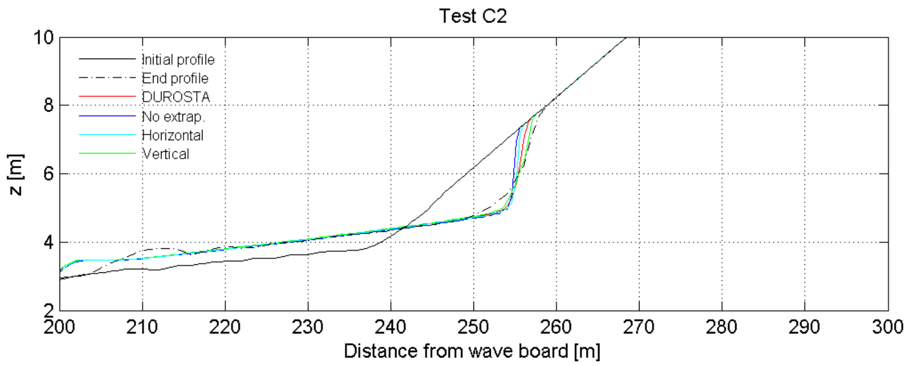
In short; the differences in mean velocity at deeper water (test T06) can not be attributed to one clear cause. Differences are a result of the summation of different smaller errors in wave height, wave celerity and water depth.

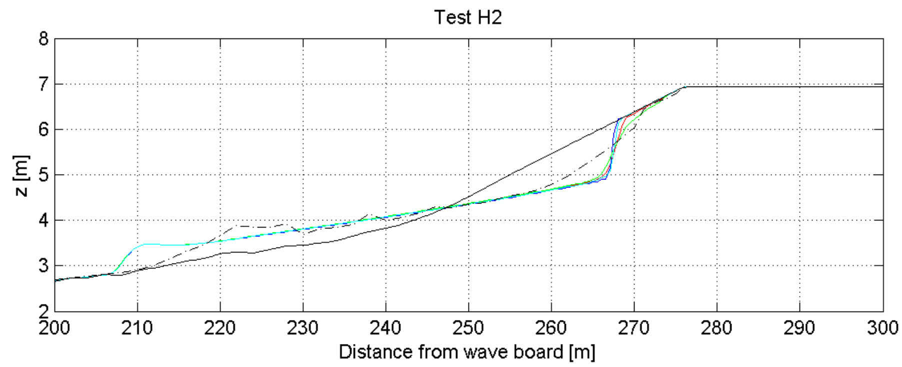
D Other important processes

D.1 Performance of extrapolation methods on GWK98 experiments

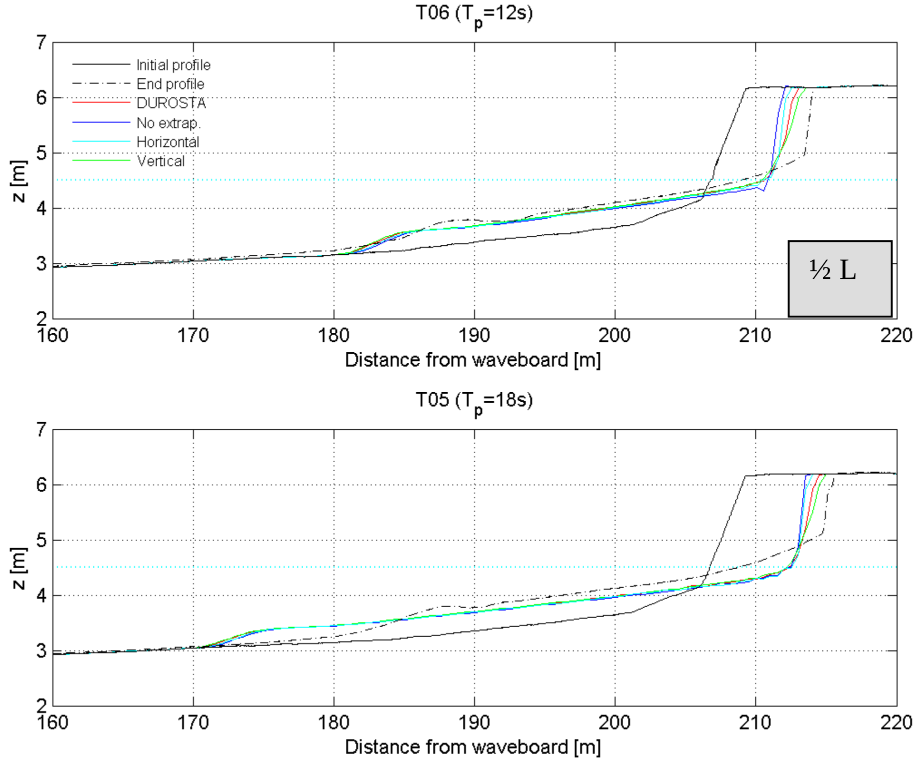


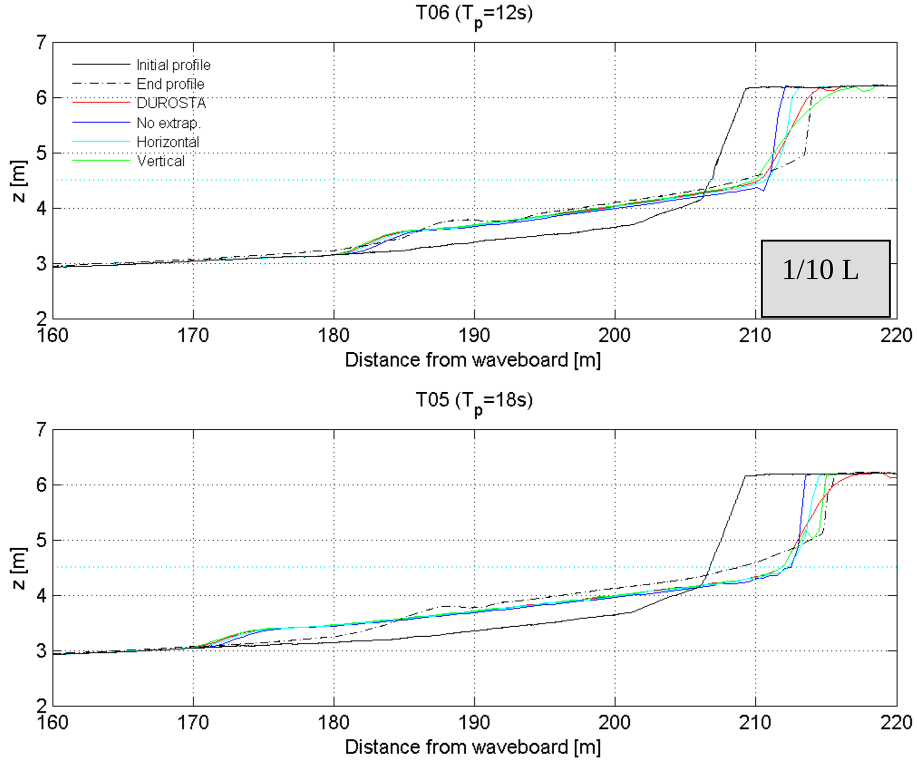


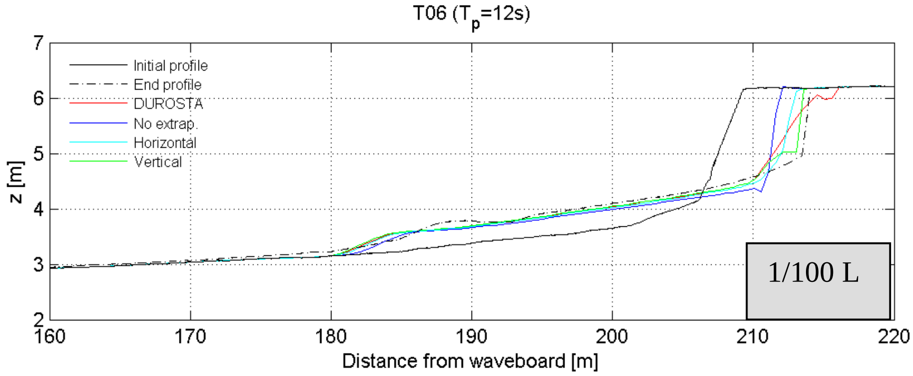


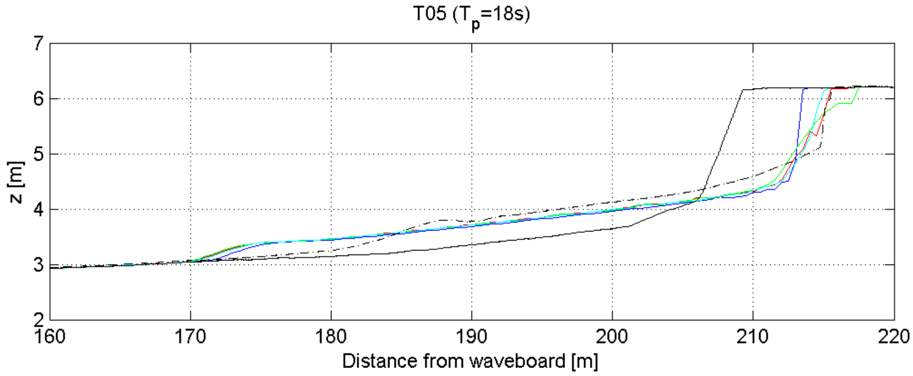


D.2 Influence of ¼ wavelength on erosion profiles

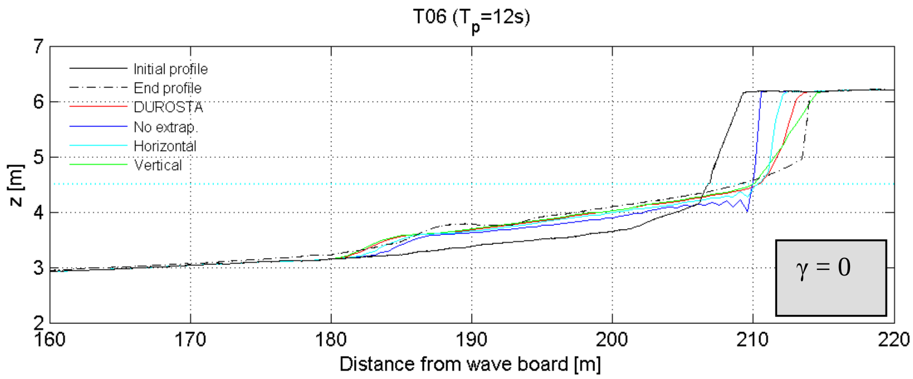


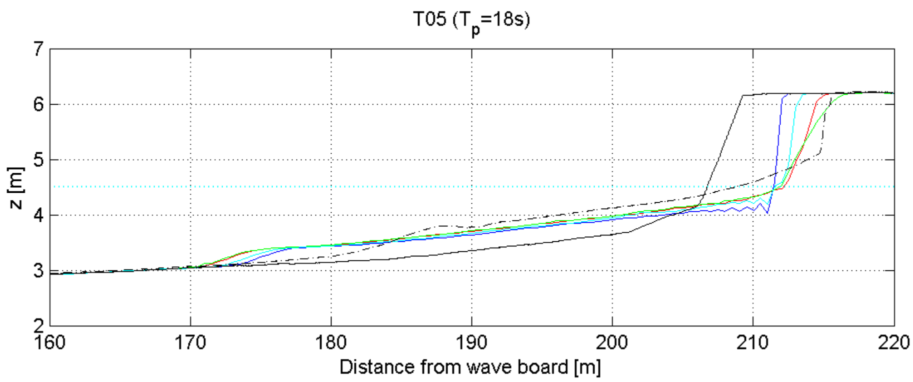


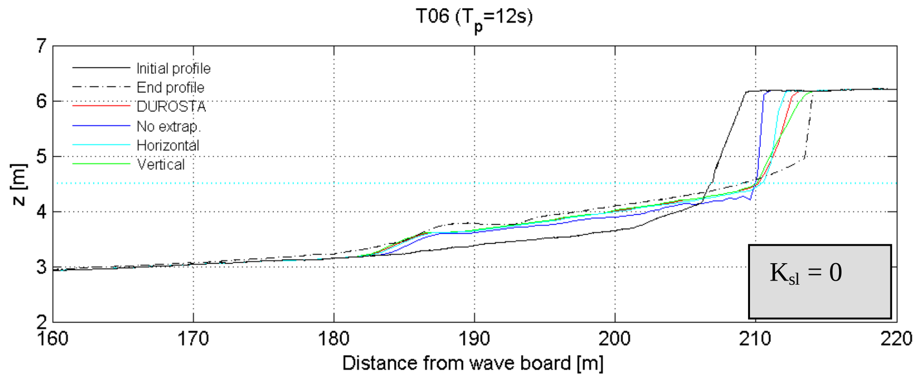


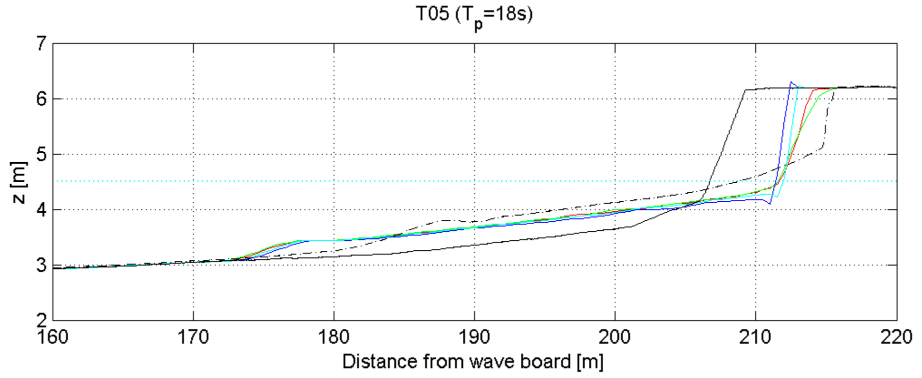


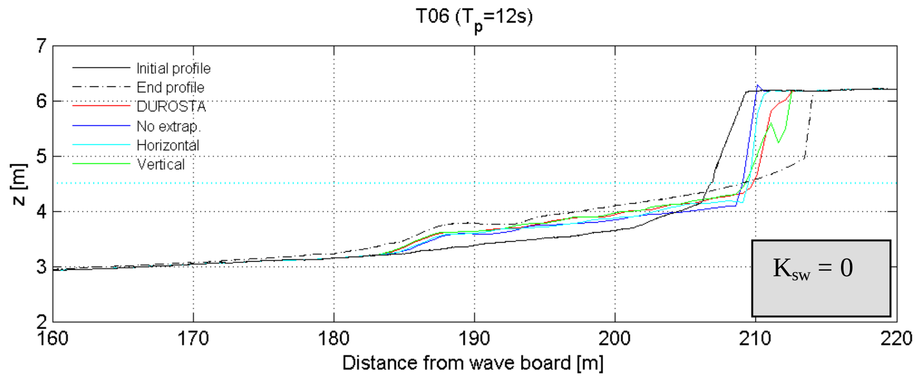
D.3 Influence of numerical smoothing and slope effects on erosion profiles

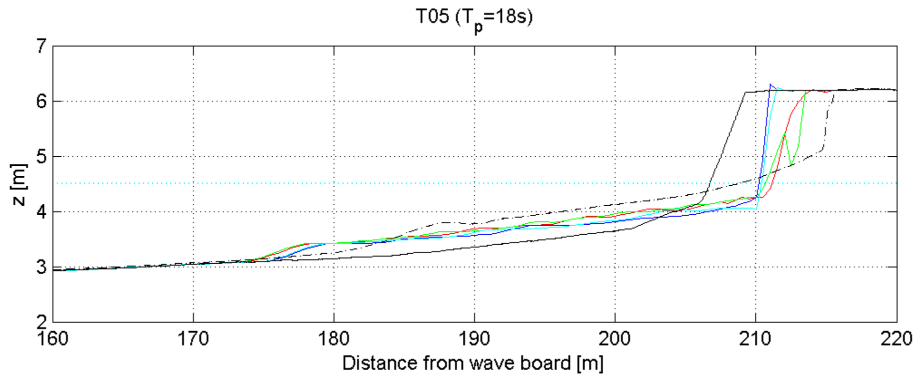


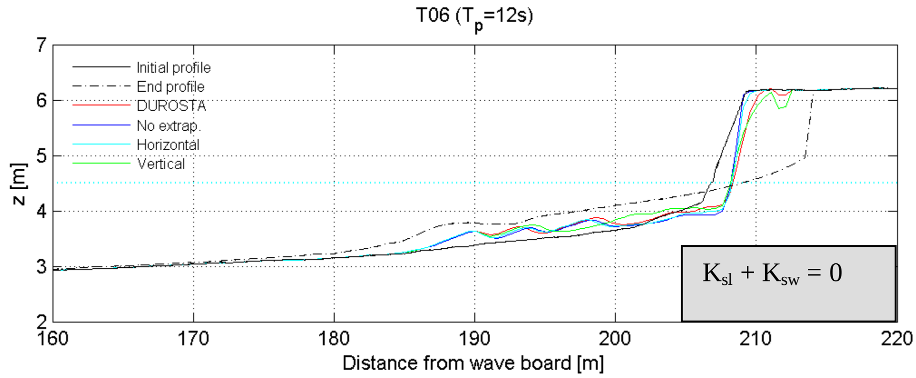


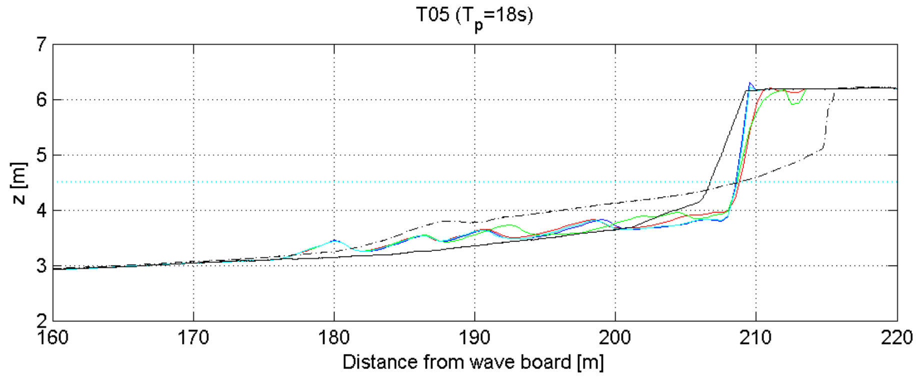

T06 (T_p=12s)
Initial profile
End profile
DUROSTA
No extrap.
Horizontal
Vertical
z [m]
Distance from wave board [m]
K_sl = 0

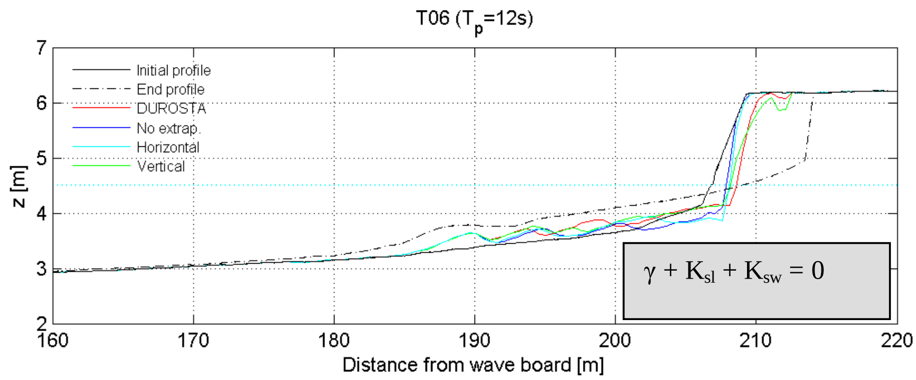

T05 (T_p=18s)
z [m]
Distance from wave board [m]

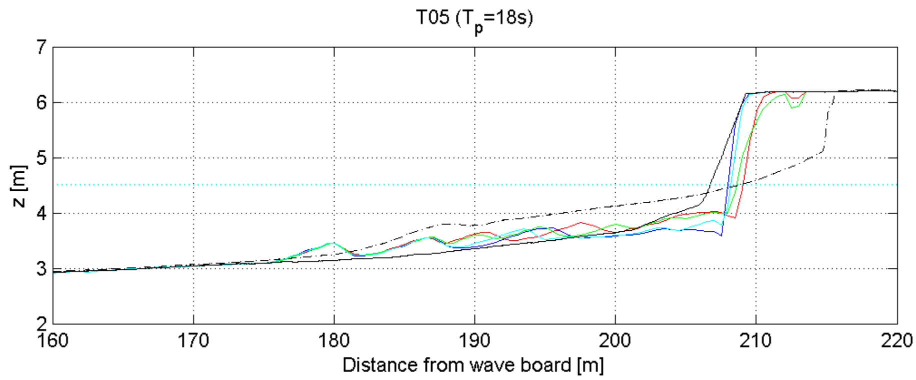

T06 (T_p=12s)
Initial profile
End profile
DUROSTA
No extrap.
Horizontal
Vertical
z [m]
Distance from wave board [m]
K_sw = 0


T05 (T_p=18s)
z [m]
Distance from wave board [m]


T06 (T_p=12s)
Initial profile
End profile
DUROSTA
No extrap.
Horizontal
Vertical
z [m]
Distance from wave board [m]
$K_{sl} + K_{sw} = 0$


T05 (T_p=18s)
z [m]
Distance from wave board [m]

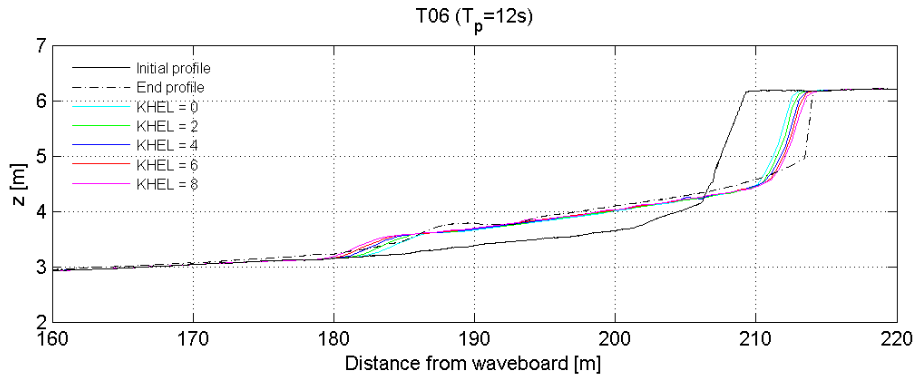

T06 (T_p=12s)
Initial profile
End profile
DUROSTA
No extrap.
Horizontal
Vertical
z [m]
Distance from wave board [m]
$\gamma + K_{sl} + K_{sw} = 0$

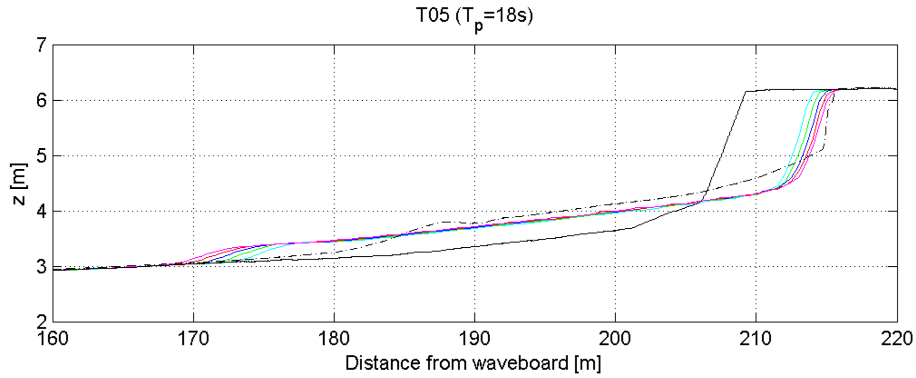

T05 (T_p=18s)
z [m]
Distance from wave board [m]

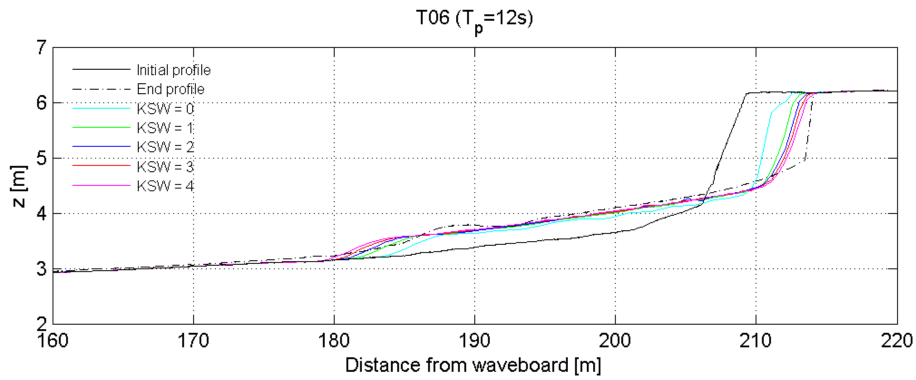
Test T06 Erosion volume [m^3/m]	No extrapolation	Horizontal extrapolation	Vertical extrapolation	DUROSTA extrapolation
Standard	6.8	7.4	8.0	7.7
DIF=0	5.2	6.7	8.0	7.6
KHEL=0	5.0	6.4	7.0	6.8
KSW=0	4.0	4.4	5.8	5.6
KSW+KHEL=0	2.7	2.7	3.3	3.1
KSW+KHEL+DIF=0	2.3	2.7	3.3	3.2
Measured	8.8			

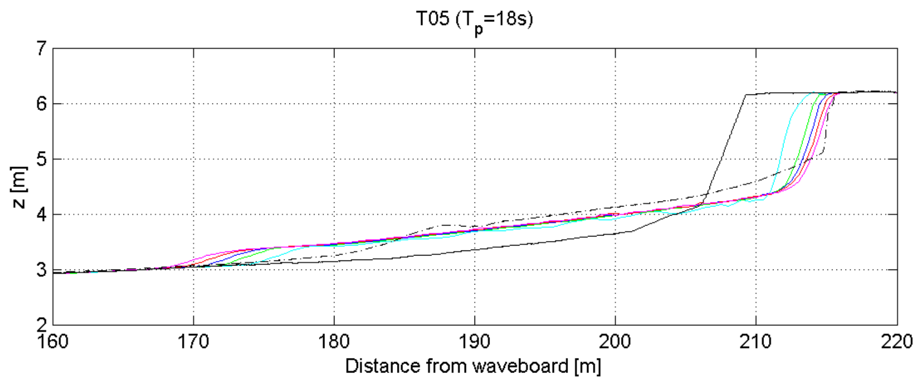
Test T05 Erosion volume [m^3/m]	No extrapolation	Horizontal extrapolation	Vertical extrapolation	DUROSTA extrapolation
Standard	10.1	10.5	11.2	10.9
DIF=0	8.5	9.5	11.1	10.7
KHEL=0	8.5	9.2	9.9	9.7
KSW=0	6.5	6.8	8.9	8.5
KSW+KHEL=0	4.4	4.4	4.7	4.7
KSW+KHEL+DIF=0	3.9	3.9	4.7	4.8
Measured	10.1			

D.4 Influence of magnitude of K_{sl} and K_{sw}

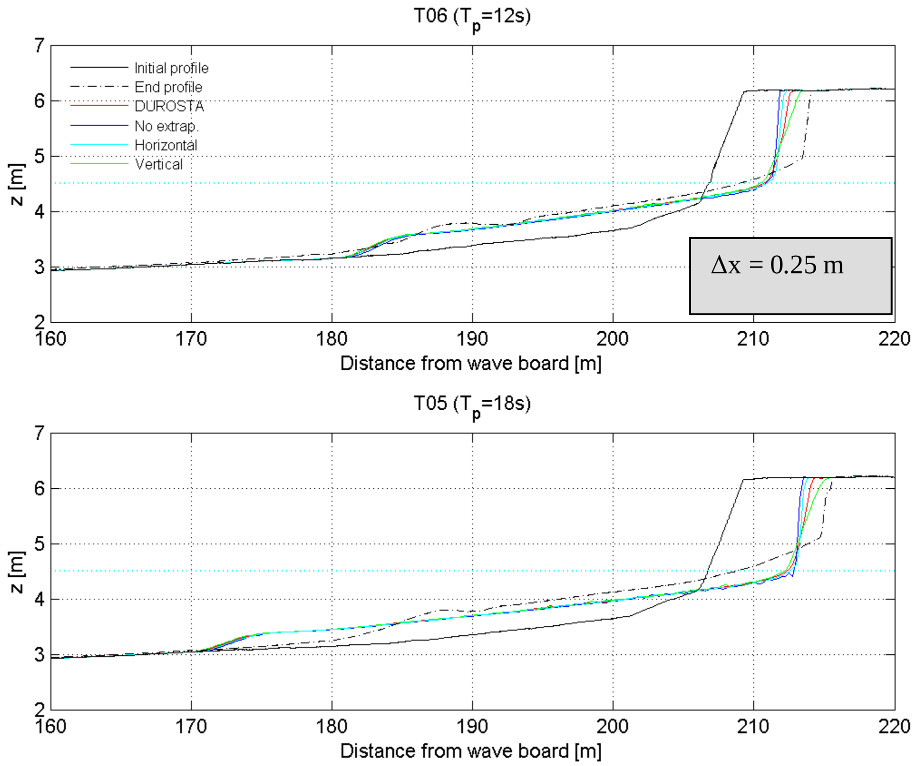


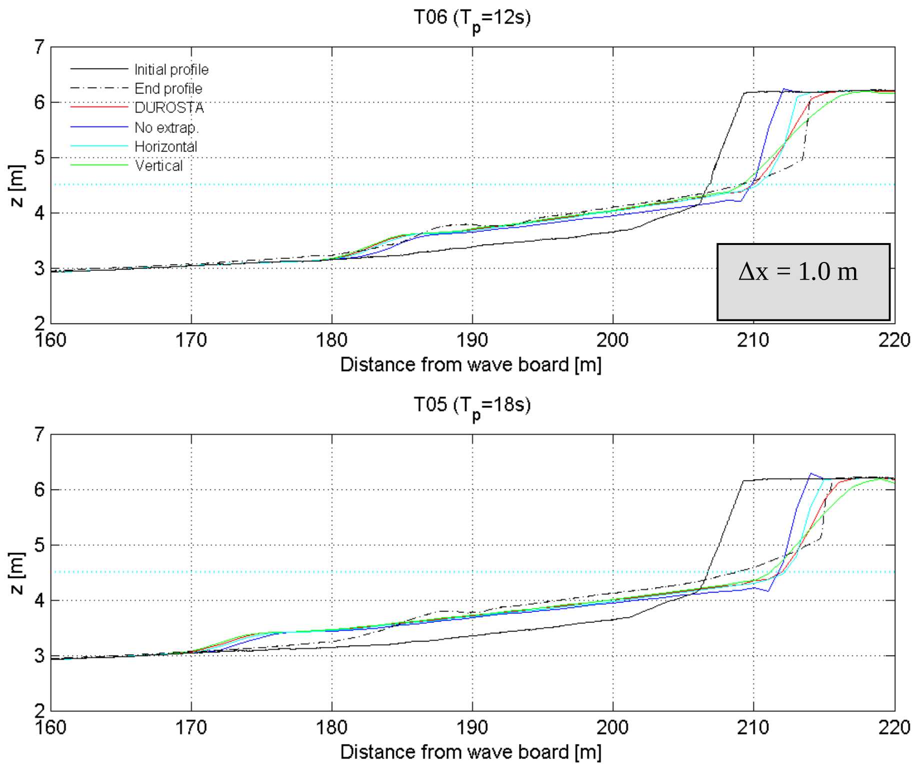






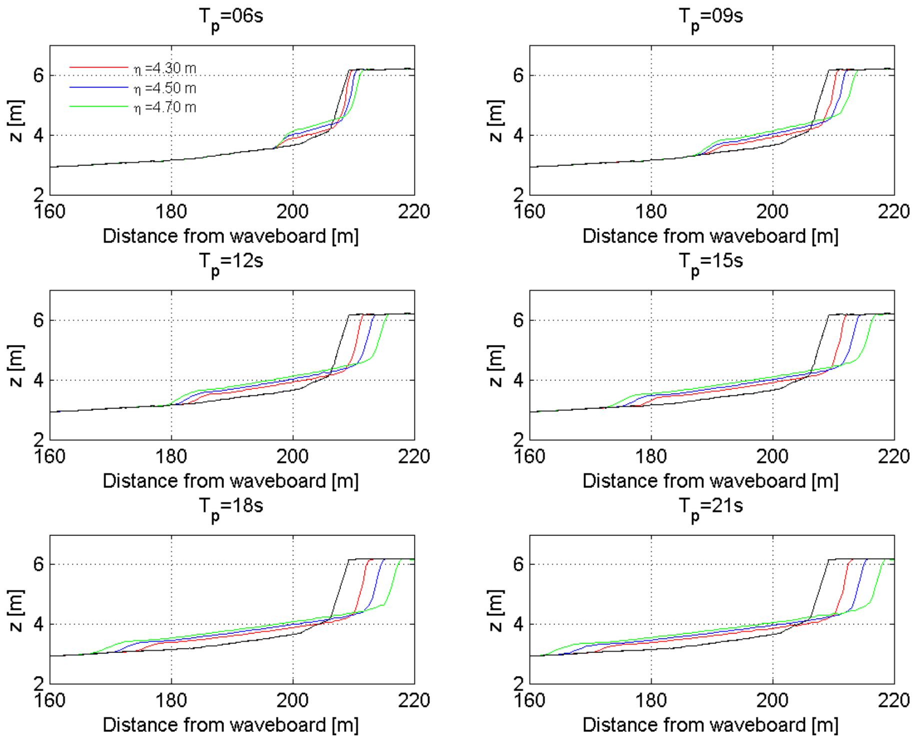
D.5 Influence of grid size on erosion profiles



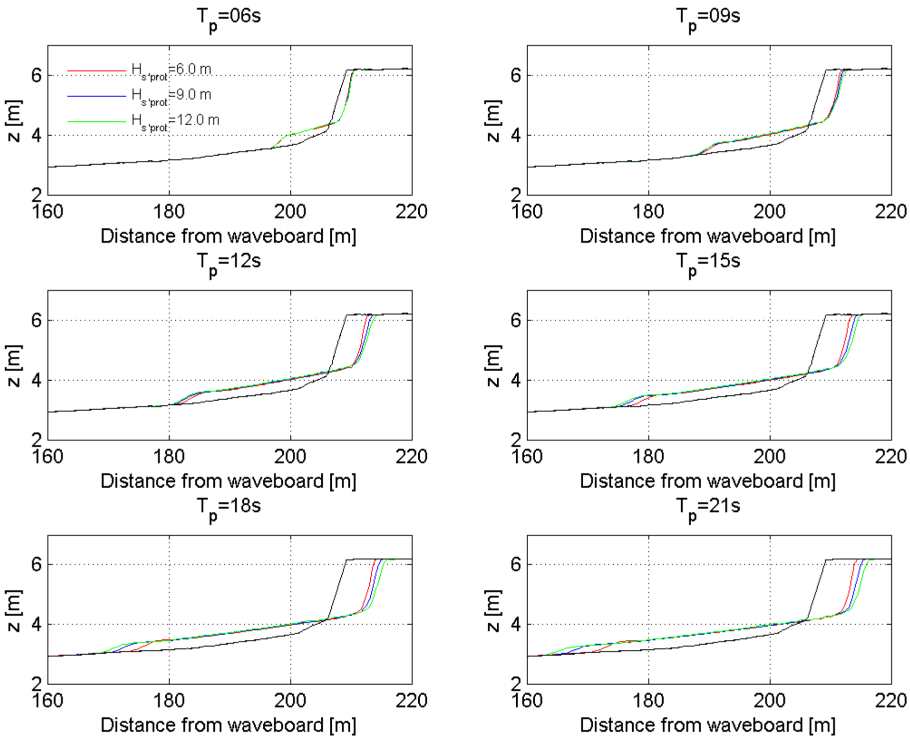


E Sensitivity analysis

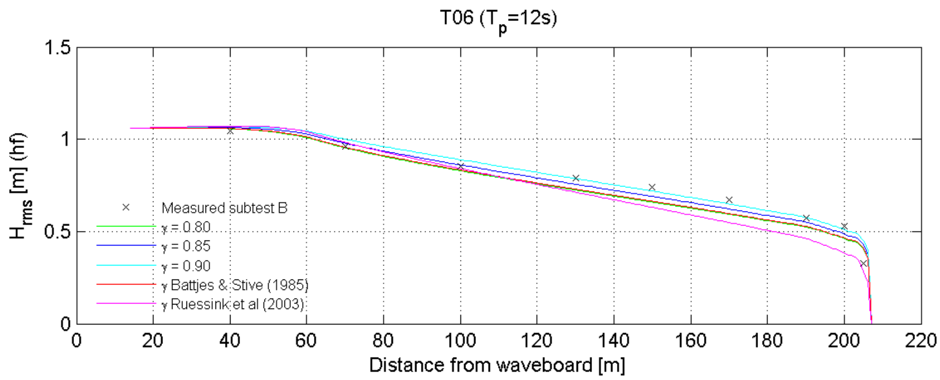
E.1 Influence of water level on erosion profiles

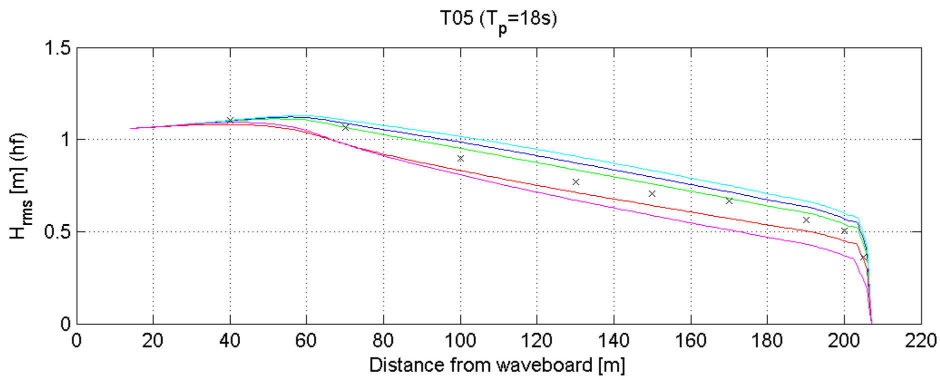


E.2 Influence of wave height on erosion volumes

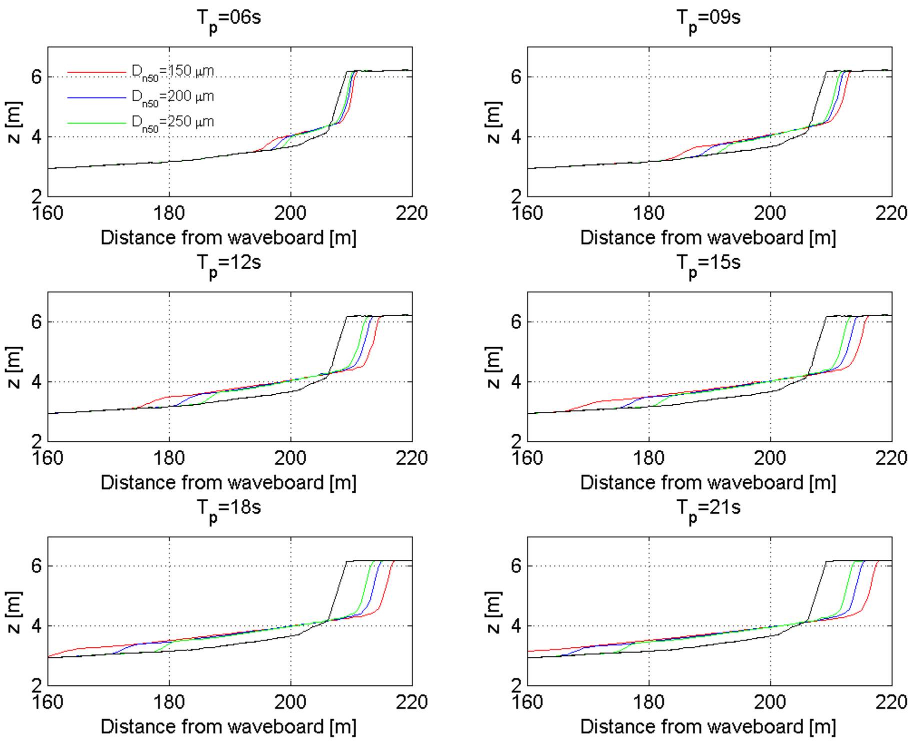


E.3 Wave height for breaker index of Battjes and Stive (1985) and Ruessink *et al*. (2003)

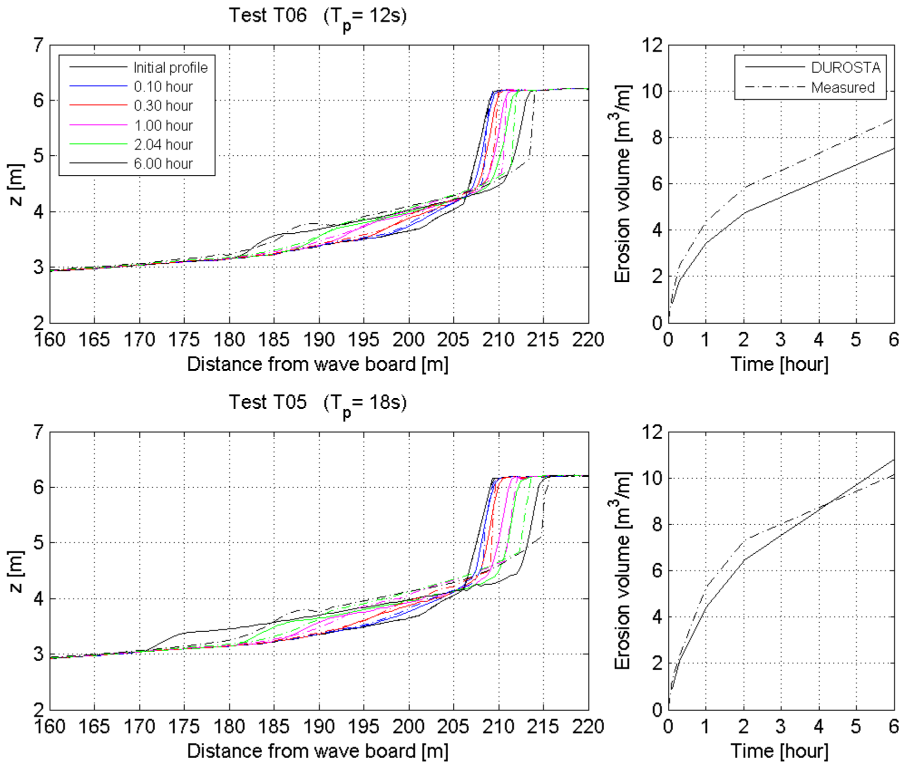


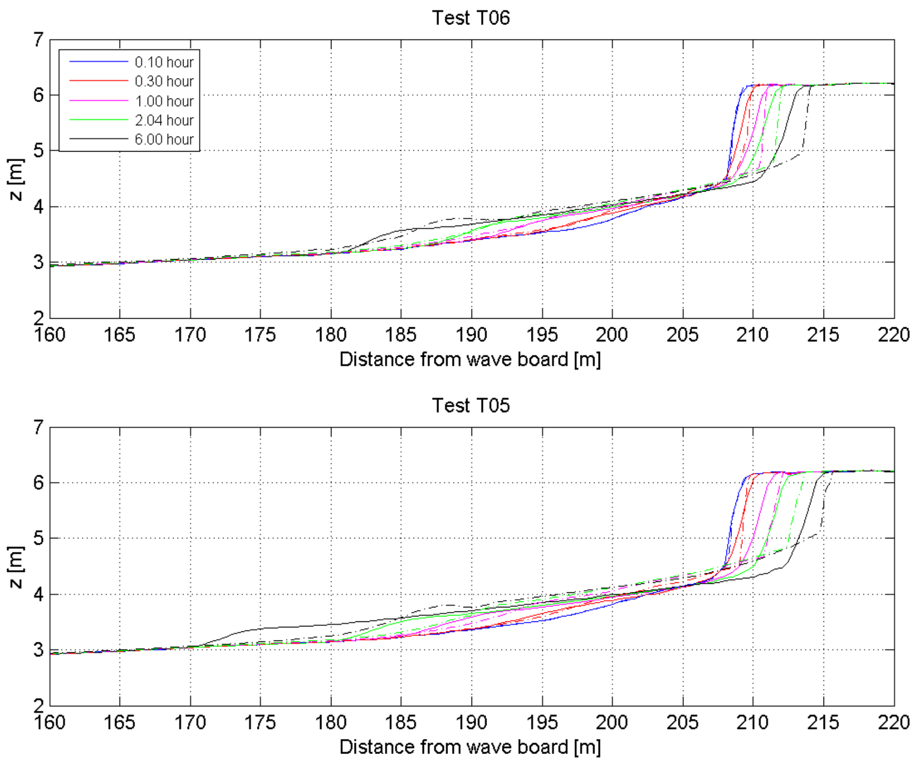


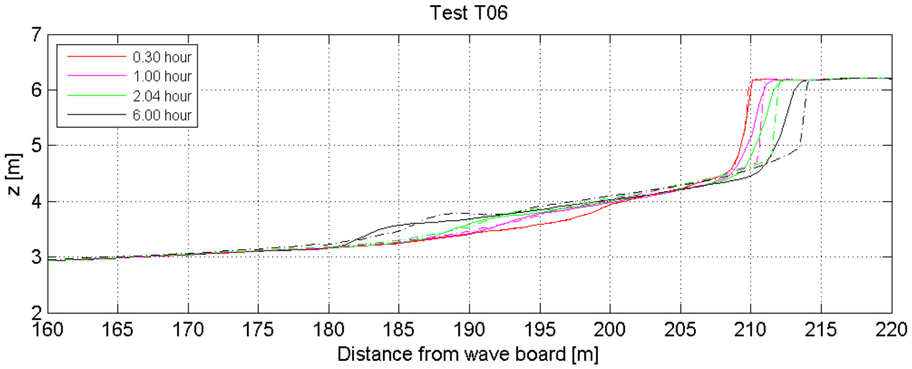
E.4 Influence of grain size on erosion profiles

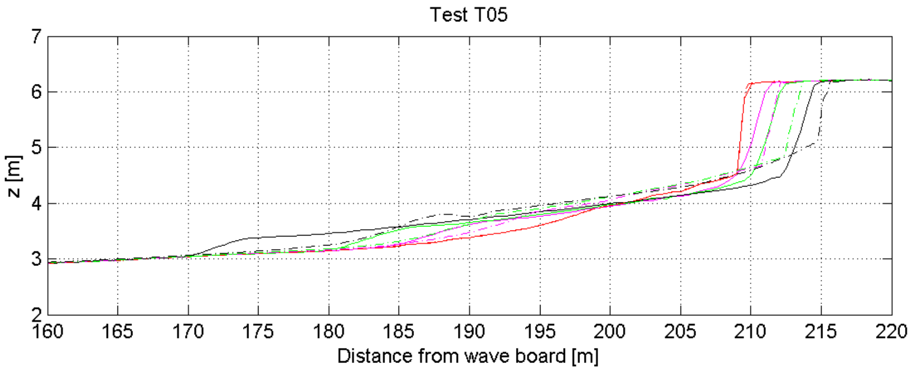


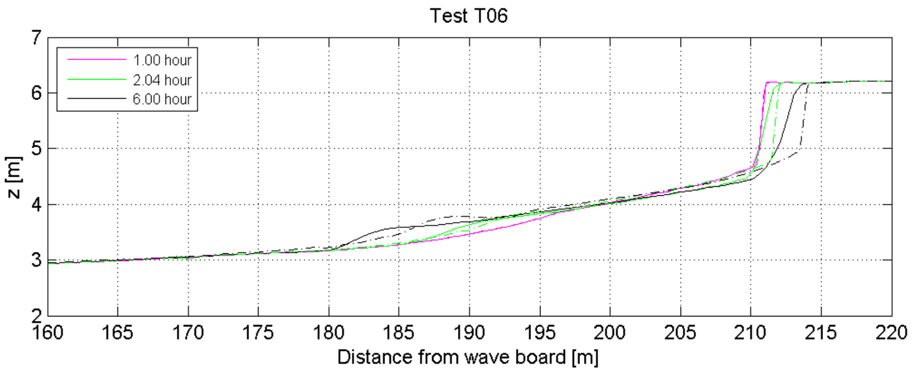
E.5 Influence of initial profile on profile development

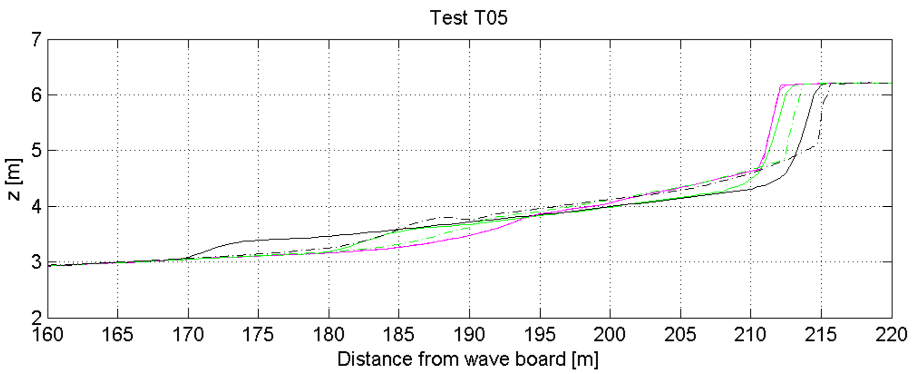


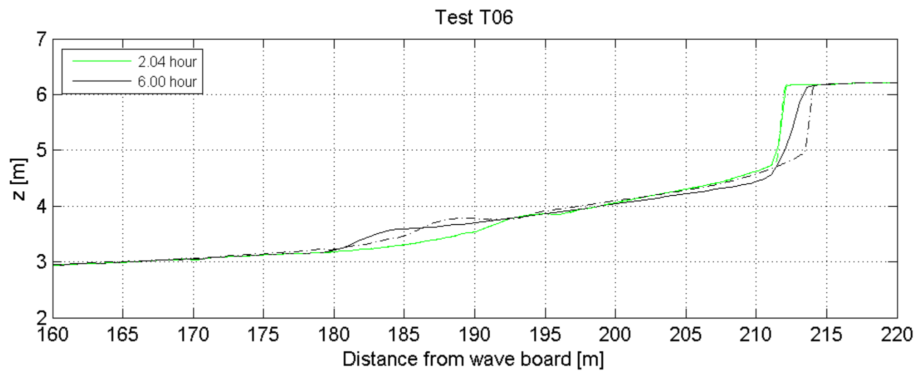


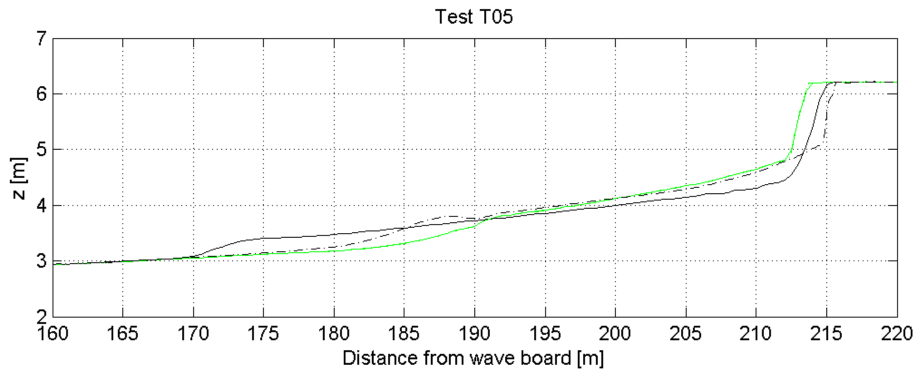

Test T06
0.30 hour
1.00 hour
2.04 hour
6.00 hour
z [m]
Distance from wave board [m]


Test T05
z [m]
Distance from wave board [m]


Test T06
1.00 hour
2.04 hour
6.00 hour
z [m]
Distance from wave board [m]

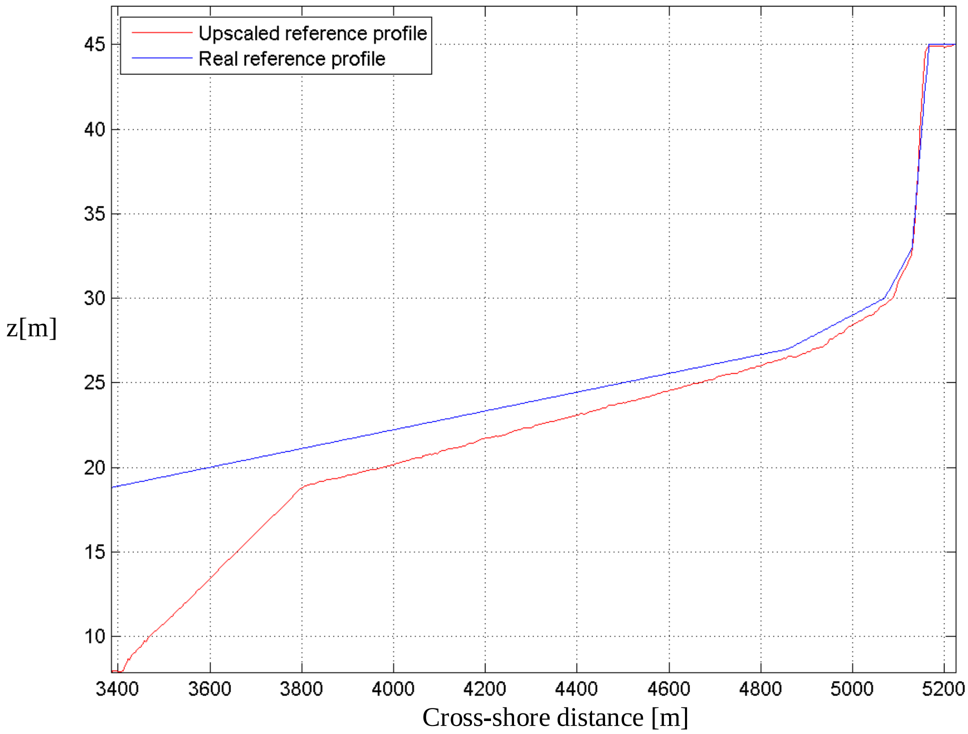

Test T05
z [m]
Distance from wave board [m]


Test T06
2.04 hour
6.00 hour
z [m]
Distance from wave board [m]

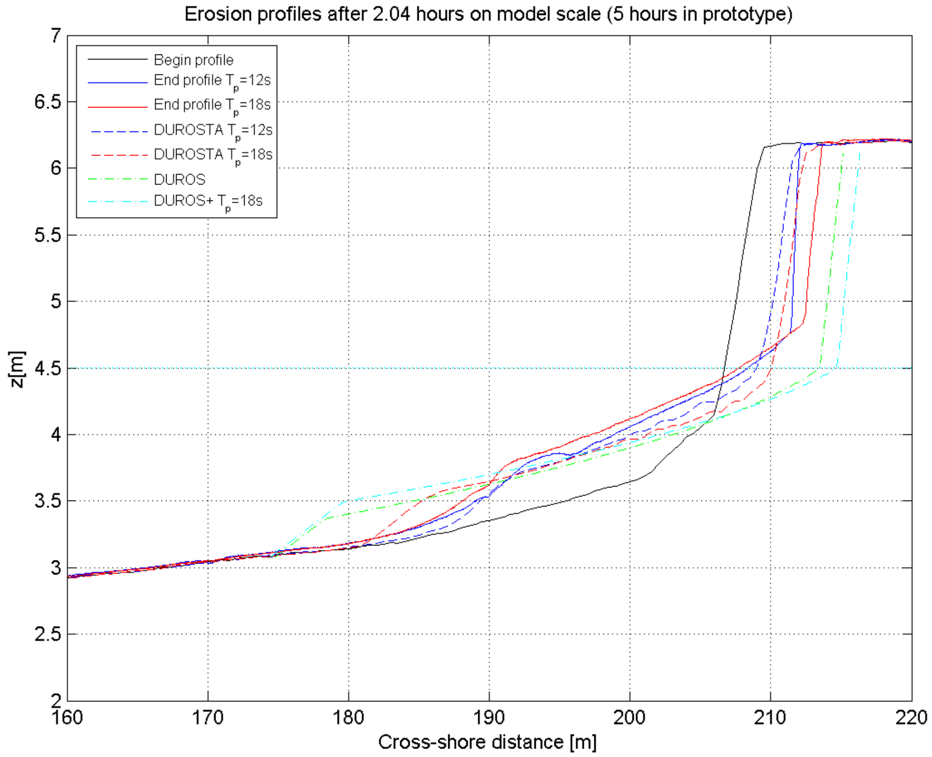

Test T05
z [m]
Distance from wave board [m]

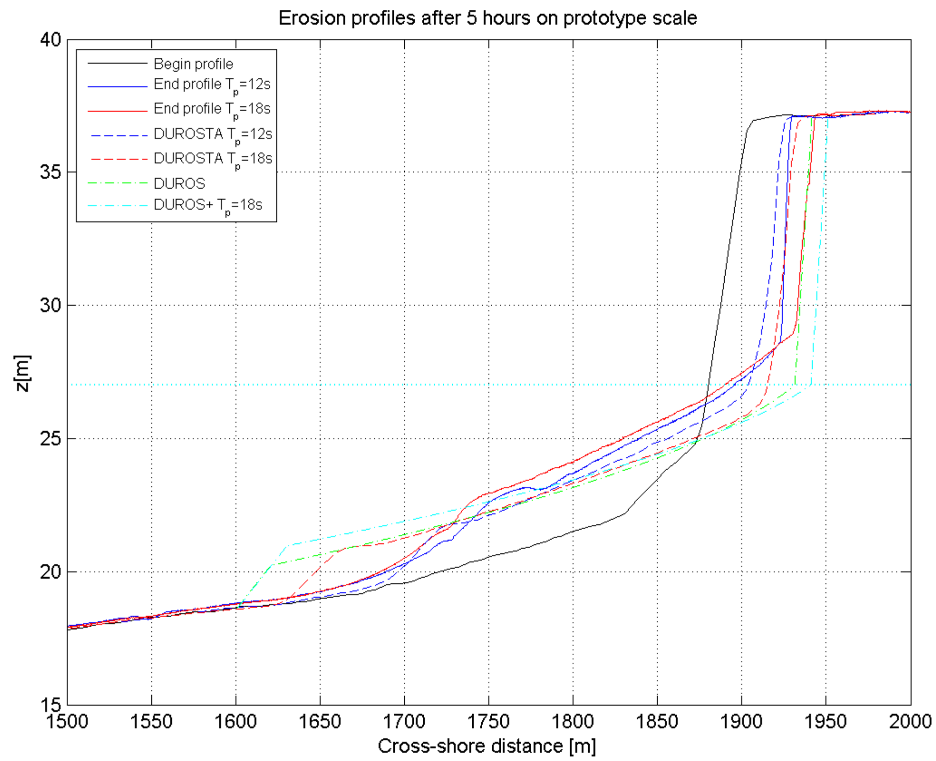
F Simulations on prototype scale

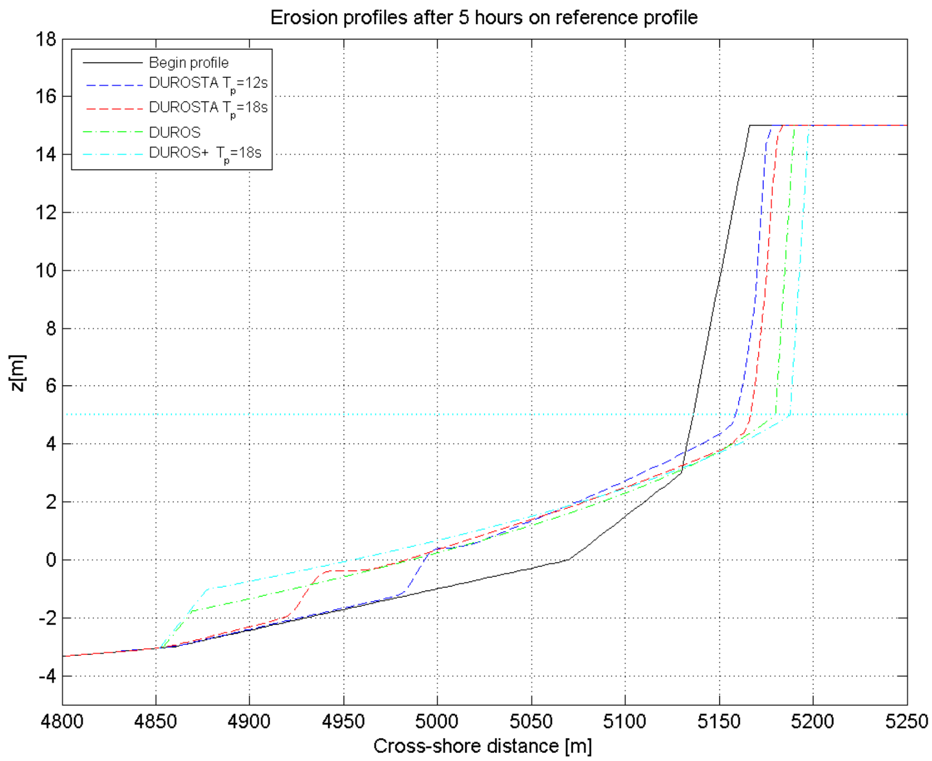
F.1 Comparison up-scaled reference profile and real reference profile



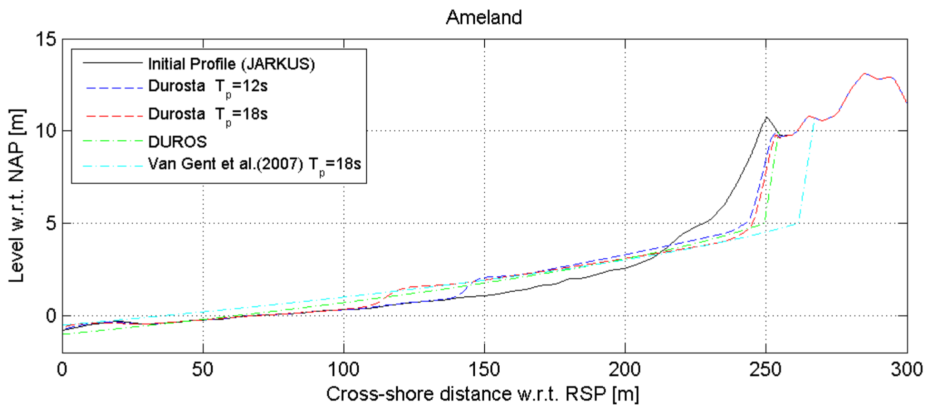
F.2 Simulations for the reference profile of the Dutch coast

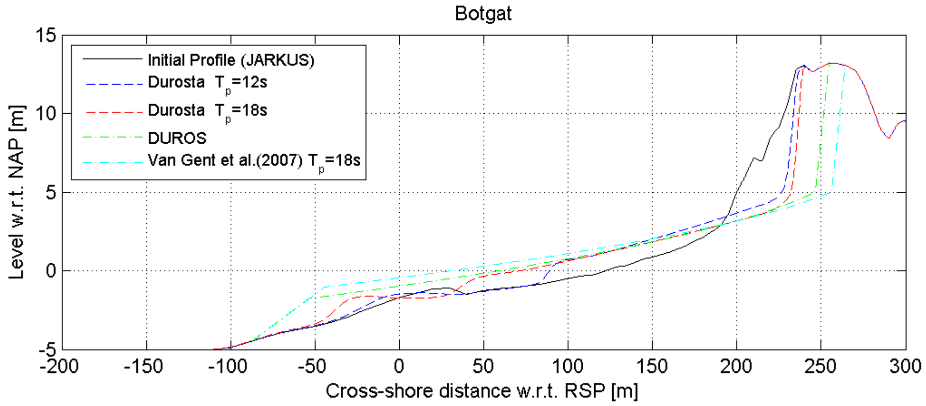


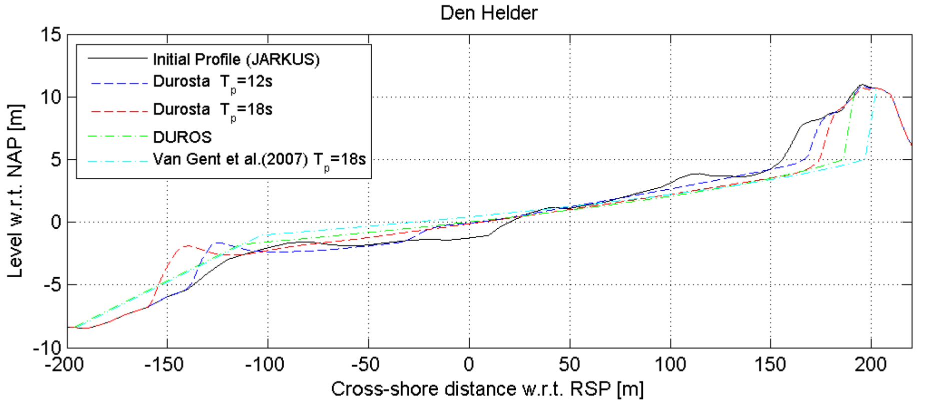


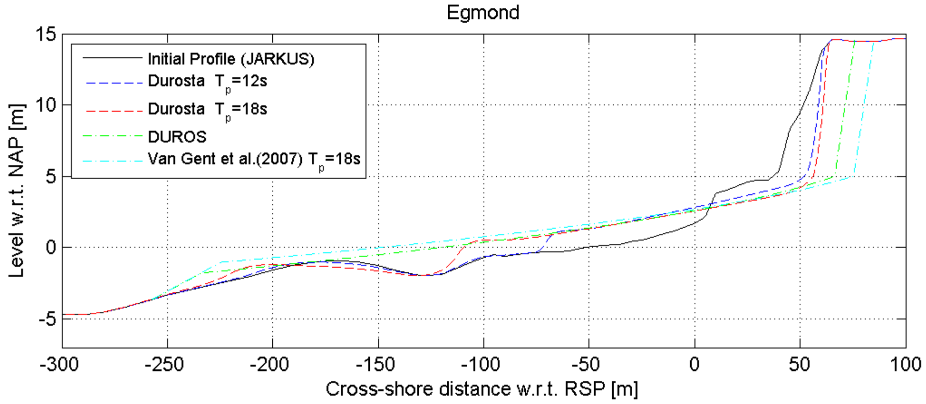


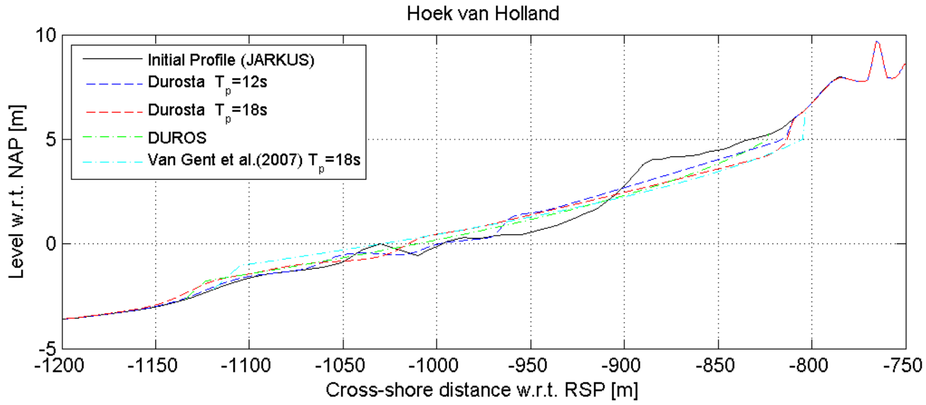
F.3 Simulations for real dune profiles measured along the Dutch coast

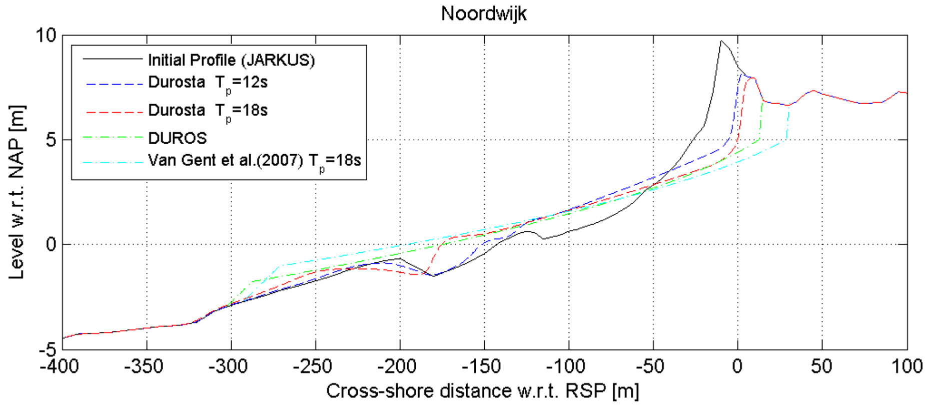


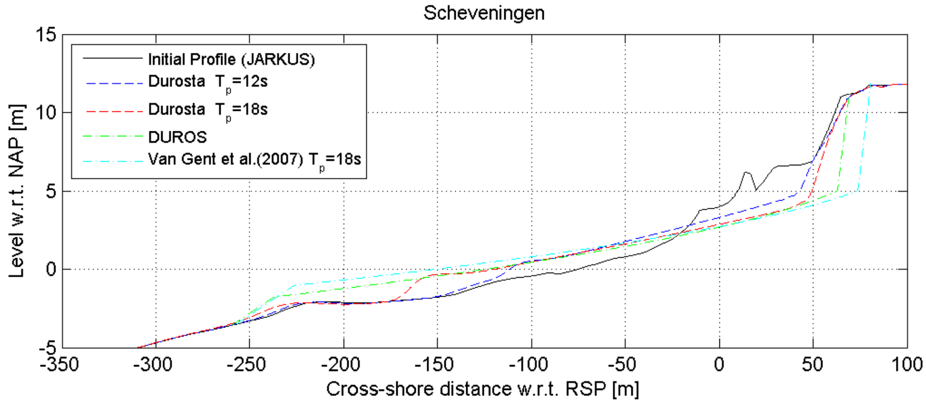

Botgat
Initial Profile (JARKUS)
Durosta T_p=12s
Durosta T_p=18s
DUROS
Van Gent et al.(2007) T_p=18s
Level w.r.t. NAP [m]
Cross-shore distance w.r.t. RSP [m]

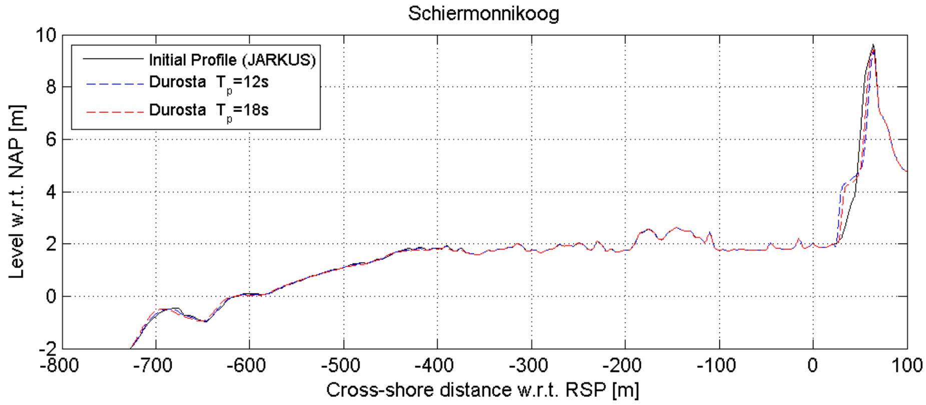

Den Helder
Initial Profile (JARKUS)
Durosta T_p=12s
Durosta T_p=18s
DUROS
Van Gent et al.(2007) T_p=18s
Level w.r.t. NAP [m]
Cross-shore distance w.r.t. RSP [m]

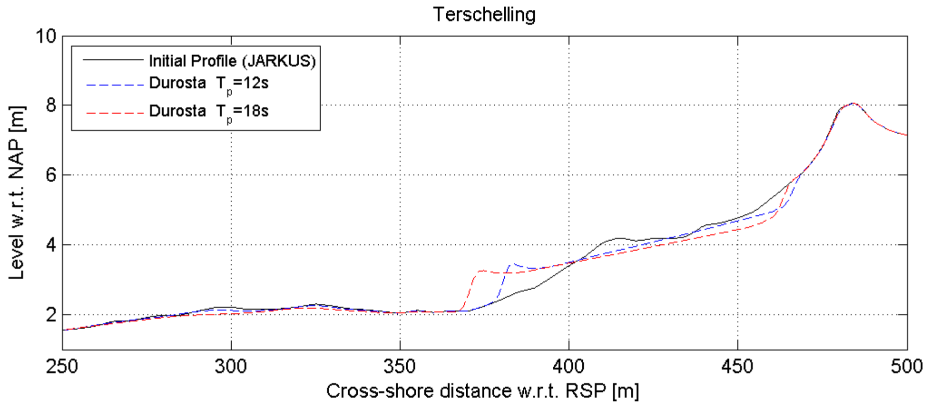

Egmond
Initial Profile (JARKUS)
Durosta T_p=12s
Durosta T_p=18s
DUROS
Van Gent et al.(2007) T_p=18s
Level w.r.t. NAP [m]
Cross-shore distance w.r.t. RSP [m]

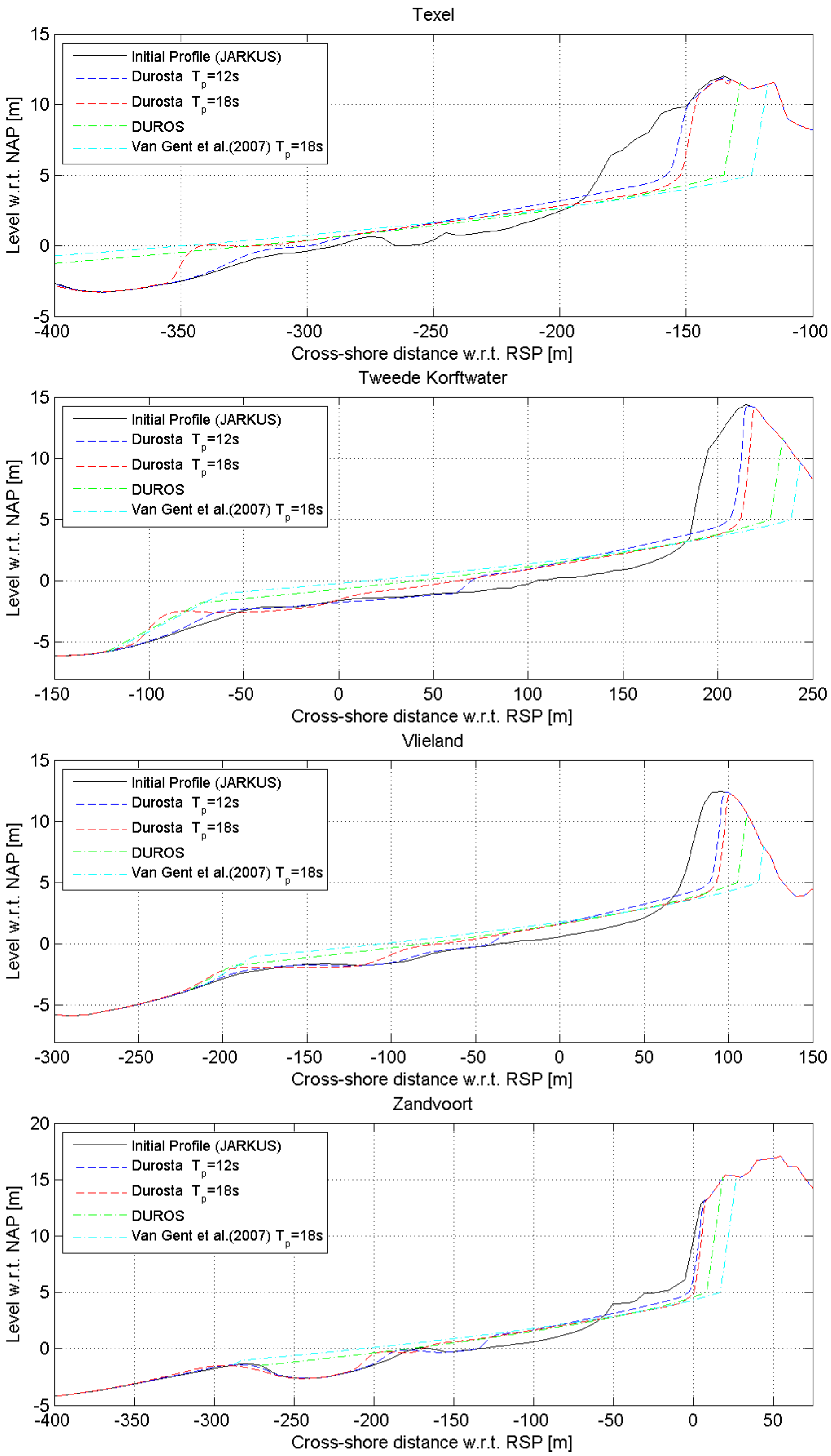

Hoek van Holland
Initial Profile (JARKUS)
Durosta T_p=12s
Durosta T_p=18s
DUROS
Van Gent et al.(2007) T_p=18s
Level w.r.t. NAP [m]
Cross-shore distance w.r.t. RSP [m]

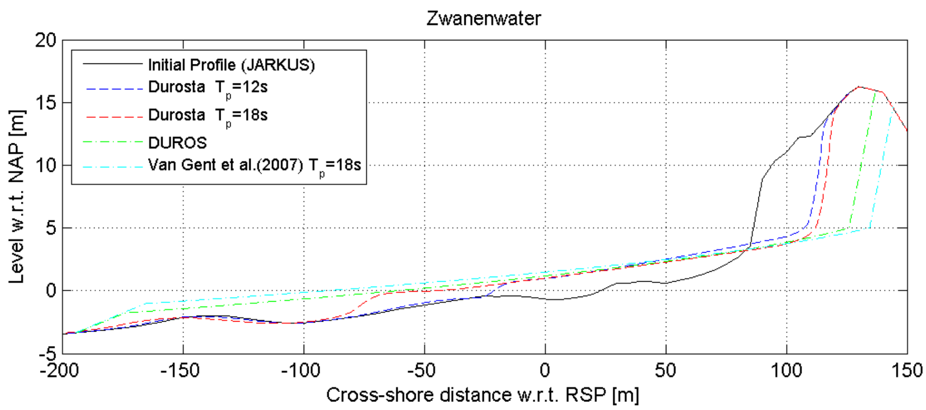

Noordwijk
Initial Profile (JARKUS)
Durosta T_p=12s
Durosta T_p=18s
DUROS
Van Gent et al.(2007) T_p=18s
Level w.r.t. NAP [m]
10
5
0
-5
-400
-350
-300
-250
-200
-150
-100
-50
0
50
100
Cross-shore distance w.r.t. RSP [m]


Scheveningen
Initial Profile (JARKUS)
Durosta T_p=12s
Durosta T_p=18s
DUROS
Van Gent et al.(2007) T_p=18s
Level w.r.t. NAP [m]
15
10
5
0
-5
-350
-300
-250
-200
-150
-100
-50
0
50
100
Cross-shore distance w.r.t. RSP [m]


Schiermonnikoog
Initial Profile (JARKUS)
Durosta T_p=12s
Durosta T_p=18s
Level w.r.t. NAP [m]
10
8
6
4
2
0
-2
-800
-700
-600
-500
-400
-300
-200
-100
0
100
Cross-shore distance w.r.t. RSP [m]


Terschelling
Initial Profile (JARKUS)
Durosta T_p=12s
Durosta T_p=18s
Level w.r.t. NAP [m]
10
8
6
4
2
250
300
350
400
450
500
Cross-shore distance w.r.t. RSP [m]


Texel
Tweede Korftwater
Vlieland
Zandvoort
Initial Profile (JARKUS)
Durosta T_p=12s
Durosta T_p=18s
DUROS
Van Gent et al.(2007) T_p=18s
Level w.r.t. NAP [m]
Cross-shore distance w.r.t. RSP [m]


Zwanenwater
Initial Profile (JARKUS)
Durosta T_p=12s
Durosta T_p=18s
DUROS
Van Gent et al.(2007) T_p=18s
Level w.r.t. NAP [m]
Cross-shore distance w.r.t. RSP [m]
20
15
10
5
0
-5
-200
-150
-100
-50
0
50
100
150